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Summary Assessment of Solar Thermal Parabolic Dish Technology for Electrical Power Generation

P.L. Panda
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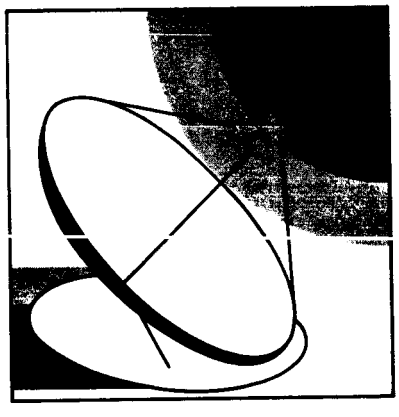

September 15, 1985

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
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ABSTRACT

An assessment is provided of solar thermal parabolic dish technology for electrical power generation. The assessment is based on the development program undertaken by the Jet Propulsion Laboratory for the U.S. Department of Energy and covers the period from the initiation of the program in 1976 through mid-1984. The program was founded on developing components and subsystems that are integrated into parabolic dish power modules for test and evaluation. The status of the project is summarized in terms of results obtained through testing of modules, and the implications of these findings are assessed in terms of techno-economic projections and market potential. The techno-economic projections are based on continuation of an evolutionary technological development program and are anchored to the accomplishments of the program as of mid-1984. The accomplishments of the development effort are summarized for each major subsystem including concentrators, receivers, and engines. The ramifications of these accomplishments are assessed in the context of developmental objectives and strategies.

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ACRONYMS

AGT	advanced gas turbine
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
ESOR	Experimental Solar-Only Receiver
FACC	Ford Aerospace and Communications Corporation
GE	General Electric Company
IPH	Industrial Process Heat
JPL	Jet Propulsion Laboratory
LeRC	NASA Lewis Research Center
NASA	National Aeronautics and Space Administration
O&M	Operating and Maintenance
ORC	Organic Rankine Cycle
PCM	Phase-Change Material
PCU	Power Conversion Unit or Power Conversion Subsystem (PCS), i.e., engine plus alternator and/or rectifier
PDC	Parabolic Dish Concentrator
PDTS	Parabolic Dish Test Site
PKI	Power Kinetics, Inc.
PON	Program Opportunity Notice
RFP	Request for Proposal
SABC	subatmospheric Brayton cycle
SAGT	Solarized Advanced Gas Turbine
SCSE	Small Community Solar Thermal Power Experiment
SERI	Solar Energy Research Institute
SNETCO	Southern New England Telephone Company
SNLA	Sandia National Laboratories, Albuquerque, New Mexico
TBC	test bed concentrator
TPS	Solar Thermal Power Systems Project at JPL
USAB	United Stirling AB of Sweden

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SECTION I

INTRODUCTION

A. THE NATIONAL SOLAR THERMAL PROGRAM

Solar thermal technologies produce heat from the sun's radiant energy for a variety of uses including electric power generation, process heat for industrial and agricultural applications, and photo/thermochemical production. The U.S. Department of Energy's (DOE) Solar Thermal Program, to implement Congressional legislation enacted in 1974 that established a national solar energy policy, instituted specific objectives including (1) completion of research and development required to support the near-term needs of industry and utilities for electricity, cogeneration, and process heat applications and (2) completion of research and development needed to expand the technology base of solar thermal energy into new industrial application areas, such as the production of fuels and chemicals. The strategy for meeting these objectives is "a program of government-sponsored and cost-shared research and development aimed at achieving a sufficient level of technical maturity for the various solar thermal technologies [so] that decision makers within the private sector will find acceptable risks should they choose to manufacture, market, or use the technologies" (Reference 1).

B. JET PROPULSION LABORATORY'S ROLE

Technical direction of the Solar Thermal Program is carried out for DOE by a network of national laboratories, which manage work done by private industry under contract or in cost-shared partnership (Table 1-1). From

Table 1-1. Solar Thermal Program Laboratory Network (Circa 1983)

Organization	Area of Responsibility
DOE San Francisco Operations Office, San Francisco, California	Fuels and Chemicals
Jet Propulsion Laboratory, Pasadena, California	Parabolic Dish-Electric Module Development
Sandia National Laboratories, Albuquerque, New Mexico	Parabolic Trough and Thermal Dish Development
Sandia National Laboratories, Livermore, California	Central Receiver Development
Solar Energy Research Institute, Golden, Colorado	Materials and Concentrator Research

1977 through 1983, the Jet Propulsion Laboratory (JPL) was responsible primarily for the development of parabolic dish-electric modules. This overall assessment document describes and summarizes all activities carried out at JPL under the DOE Solar Thermal Program during those years. During FY 1984, this work was phased out at JPL and at the direction of DOE was transferred to Sandia National Laboratories in Albuquerque (SNLA). This document, in addition to approximately 30 detailed reports and a complete bibliography, were published by JPL as part of the Project phaseout efforts. JPL also will continue to perform related Program tasks for SNLA.

Specifically, this overall assessment provides a narrative of the history and evolution of solar thermal work at JPL (Section I.C,D); a general system description (Section I.E); development and/or testing of dish system components including concentrators, receivers, power conversion units, energy transport, energy storage, and controls (Section II); current status of module development (Section III); and system performance and economic projections (Section IV).

C. HISTORY OF SOLAR THERMAL WORK AT JPL

The Solar Thermal Power Systems (TPS) Project at JPL was initiated in 1976 to develop solar thermal systems capable of producing thermal and electrical energy in a reliable and cost-effective manner. Studies conducted during that year under sponsorship of the National Aeronautics and Space Administration (NASA) Office of Energy Programs established point-focusing distributed receiver systems as a solar thermal approach with the potential for producing low-cost energy. From 1977 through the end of 1983, the TPS Project continued research and development of this technology as part of the national Solar Thermal Program funded by DOE's Division of Solar Thermal Technology.

The attractiveness of these point-focusing devices (called parabolic dishes because of the parabolic shape of the reflector) lies in their inherent modularity, the potential for high conversion efficiency via high concentration and high operating temperatures, two-axis tracking capability for maximum radiation collection, heat production over a wide temperature range, and mass-production possibilities.

Early Project goals included (1) the demonstration of the potential, in mass production quantities, for producing electricity or heat by point-focusing devices at a cost that is economically competitive with conventional alternatives and (2) the development of cost-effective point-focusing distributed receiver technology necessary for accelerated market penetration of small solar thermal power systems (Reference 2).

Initial studies indicated the existence of a small near-term market (1990 to 2000 time frame), known as the "isolated loads market," where the user is isolated from the electric utility distribution grid. This application is typical of small municipal communities, isolated industrial sites, other isolated sites (i.e., rural/agricultural communities, islands, and military installations), and cottage industries in developing countries. Although this market is small (300 to 1000 MWe/year) when compared to the grid-connected utility market, up to 10,000 parabolic dishes per year would be

required to meet this need -- a quantity justifying the use of mass production techniques for dish fabrication.

The projected far-term market for parabolic dishes was the U.S. grid-connected utility market. It was estimated that almost all utilities in the continental United States will be connected to an electric distribution grid by the end of this decade. For dishes to compete in the low-cost grid-connected market by the year 2000, they were to benefit from the technological experience and mass production techniques achievable through the successful penetration of the higher-cost isolated markets.

Because of the fact that two market phases (near- and far-term) were envisioned, the TPS Project structured its Technology Development Element (Figure 1-1) on the basis of two types of hardware development: first-generation and second-generation. First-generation equipment would entail fewer developmental risks and would permit the early introduction of dish power plants into the isolated loads market. The far-term market would be penetrated by dish systems using second-generation technology. These modules would benefit from advanced engine technology, improved system efficiency, innovative collector design, and increased production volume.

As shown in Figure 1-1, the Technology Development Element of the early TPS Project was complemented by two parallel spheres of activity carried out under the Advanced Development Element and the Applications Development Element. Advanced Development was oriented toward research and development, emphasizing materials, component, and subsystem development. Resulting designs were engineered, fabricated, and tested in complete module configurations through the Technology Development Element. Power plant systems were then to be assembled and demonstrated under the third Project

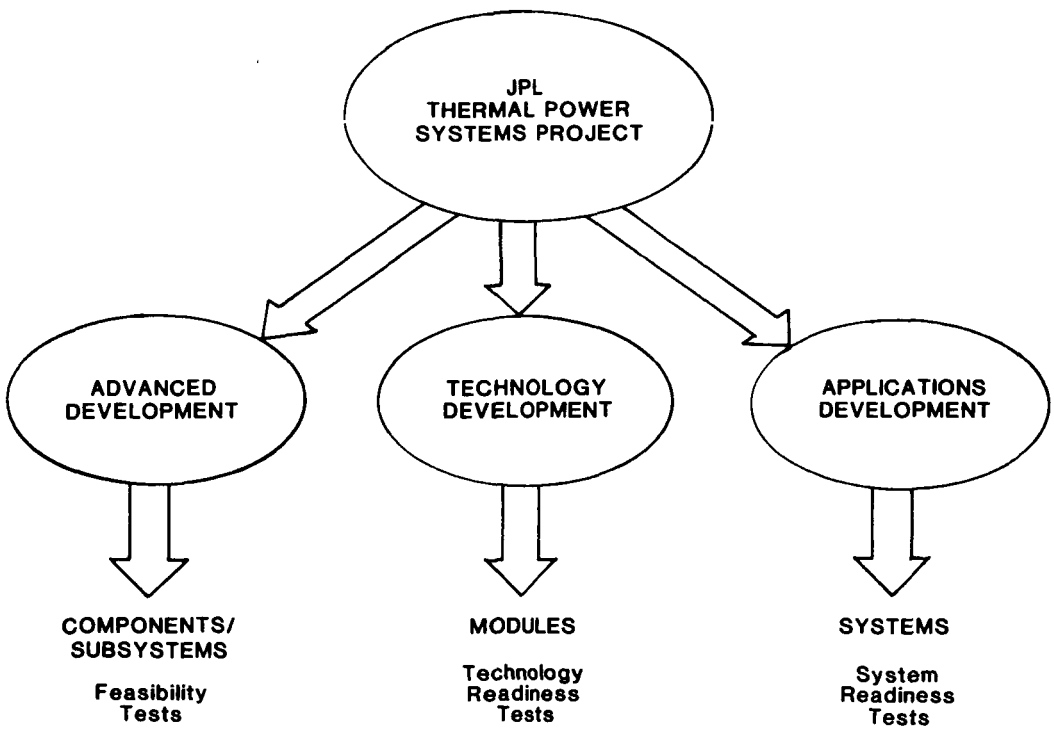

Figure 1-1. Elements of the Early Solar Thermal Power Systems Project

element through a number of engineering system experiments in a variety of user applications.

The development by the Project of both first- and second-generation technology began at approximately the same time: late 1978 and early 1979, respectively. First-generation activities would continue throughout 1983, while the evolution of second-generation hardware was to progress toward the end of the decade, during which the most promising candidates for advanced components and systems would be evaluated and tested. Two test bed concentrators (TBCs), built by E-Systems and installed in September 1979 at the JPL Edwards Test Station in the Mojave Desert, California, became the primary test vehicles (Figure 1-2) for characterizing and testing components and were also the first major pieces of equipment comprising what soon became known as the Parabolic Dish Test Site (PDTS).

During 1980 and 1981, the Advanced Development Element was called the Research and Advanced Development Element and was responsible for work on advanced[1] components, including the Acurex advanced concentrator, the United Stirling P-40 engine, the Fairchild "hybrid" receiver, and the General Electric heat pipe receiver (each discussed in Section II). This element also reported to the Solar Energy Research Institute (SERI) work done at JPL in the areas of advanced systems studies and component research and development, including transport and materials technology. In 1981, these efforts were transferred to SERI and are described in Reference 3.

Figure 1-2. Test Bed Concentrators at the Parabolic Dish Test Site

[1]The term "advanced" is synonymous with "second-generation."

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Three engineering experiments were the emphasis of the renamed Applications and Market Development Element during the early 1980s. These experiments were to demonstrate the technical and economic readiness of dish systems in electric power and process heat applications (Reference 2). Market sectors for each of the experiments are shown in Figure 1-3. The third engineering experiment (EE No. 3) was carried out by JPL up to the operational phase: A collector built by Power Kinetics, Inc. (PKI), was prototype tested and installed at the process heat user site. At that time, management of the experiment was turned over to Sandia National Laboratories in Albuquerque (see Section II.A.5.c). EE No. 2 was abandoned due to funding constraints, and EE No. 1 became the major thrust of the Applications Element. This latter experiment evolved into the Small Community Solar Thermal Power Experiment No. 1 (SCSE-1) that was to be installed at Osage City, Kansas, in 1984. JPL's participation in this experiment (Section III.A.2) continued until the fall of 1983 when DOE and Ford Aerospace and Communications Corporation (FACC), prime contractor for the organic Rankine-cycle (ORC) module,[2] were unable to complete contractual arrangements.[3]

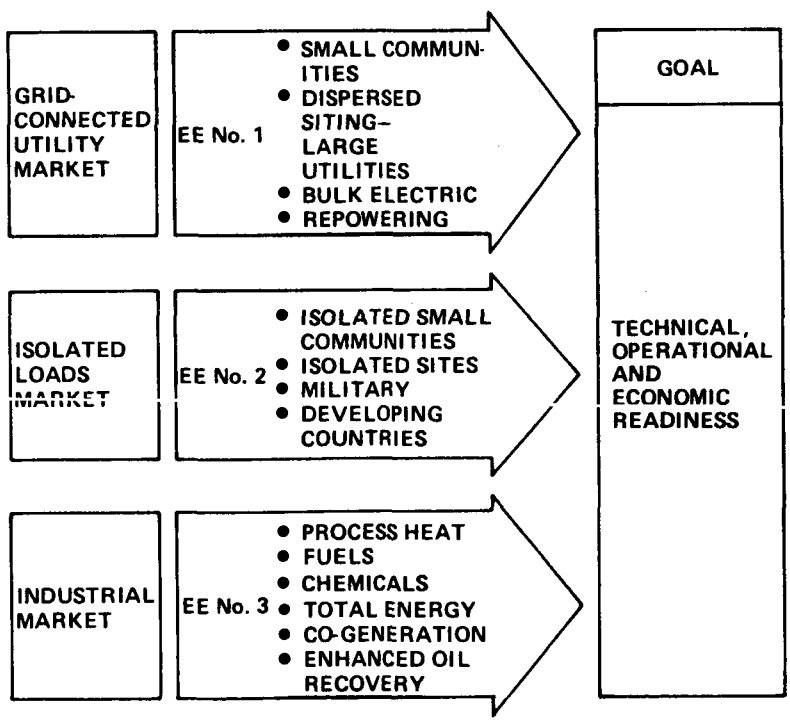

Figure 1-3. TPS Project Engineering Experiments

[2]The ORC module, development of which was managed by the TPS Project, was to be deployed as the dish system for SCSE-1.

[3]DOE resolicited bids for the experiment in December 1983.

The original Technology Development Element became the TPS Project's main vehicle for developing and/or testing dish system components and for integrating them into complete dish-electric power modules. These components (i.e., concentrators, receivers, engines, transport, storage, and controls) are discussed in detail in Section II. JPL's efforts to develop dish-electric modules based on Rankine-, Stirling-, and Brayton-cycle technology (discussed in Section III) continued until transfer of activities to Sandia National Laboratories was completed in mid-1984.

D. CURRENT MARKET PROJECTIONS

Tests conducted through 1984 by the TPS Project of modules employing Brayton, organic-Rankine, and Stirling engines indicate that early modules achieve efficiencies of 15 to 25% (sunlight to net electricity produced). Using these results as a base and projecting improvements in efficiency, operation and maintenance, and concentrator design, module costs have been determined as a function of production volume (see Section IV). Present TPS studies indicate that dish-electric modules now in the test and evaluation stage would be competitive in the isolated load markets at production levels of 100 units per year and in the small community markets at 1000 per year if fossil fuel prices rise to the upper limit presently projected. If intermediate fuel price projections are used, further advances in technology leading to higher performance and lower cost would be necessary for dish-electric modules to be competitive in the energy markets (Reference 4).

E. PARABOLIC DISH-ELECTRIC SYSTEM DESCRIPTION

A point-focusing parabolic dish system comprises one or more autonomous energy-producing units called modules. Each module includes a collector, composed of a dish-shaped parabolic concentrator (that focuses the sun's rays) plus a receiver (heat absorber) that is mounted on the dish at its focal plane, and a power conversion unit integrally joined to the receiver (Figure 1-4). The concentrated sunlight enters the receiver opening (aperture) and heats a fluid (heat transfer fluid) circulating through the receiver. The hot fluid is used to produce electricity by the power conversion unit, which typically consists of a heat engine, alternator, and associated controls. A single parabolic dish module can achieve fluid temperatures from 300 to 1500°C (572 to 2732°F) and can efficiently produce up to 25 kW of electricity. (Minimizing the cost of power results in a system about this size.) Each module is a complete electricity-producing unit, which can function autonomously either as an independent system or as part of a group of modules linked by an electrical transport network to form a power plant. Dish plants ranging in size from 10 kWe to 10 MWe or higher output power could supply cost-effective electricity to isolated communities and other small communities that are not connected to utility grids and are forced to use high-cost conventional energy supplies. A typical parabolic dish-electric power plant is shown in Figure 1-5.

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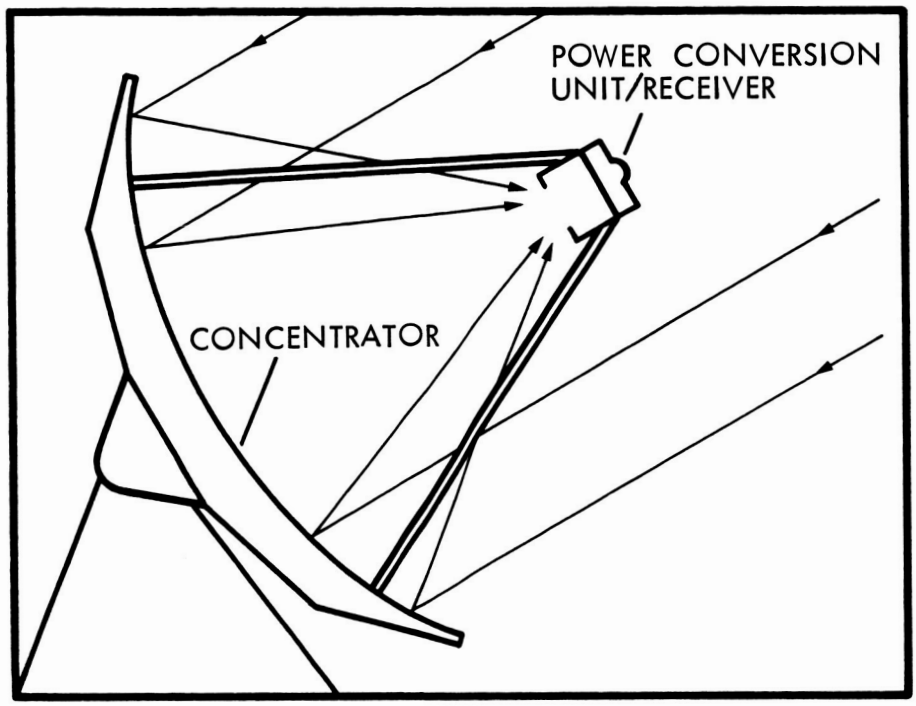

Figure 1-4. Principal Components of a Parabolic Dish-Electric Module

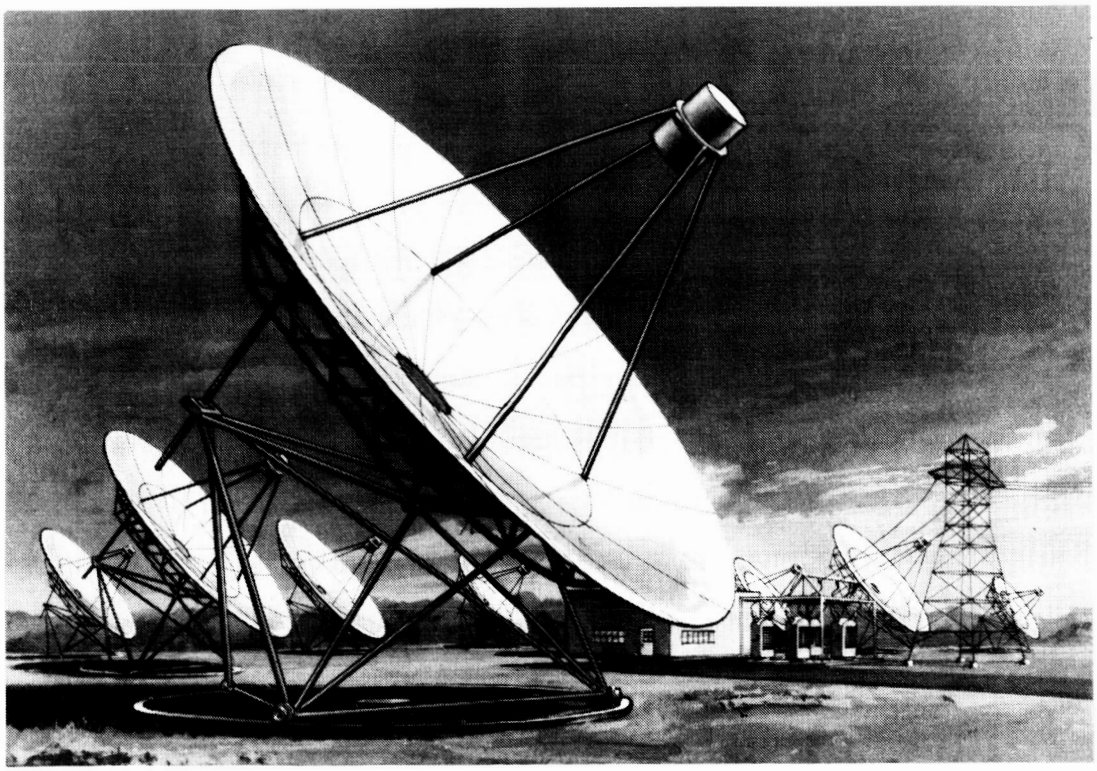

Figure 1-5. Rendering of a Typical Parabolic Dish-Electric Power Plant

Dish collectors track the sun in two directions (axes) so that the reflective surface of the concentrator can continuously face the sun at the optimal angle for maximum heat collection. Two-axis tracking is usually accomplished by using an azimuth-elevation mount, where the concentrator rotates about a vertical axis for alignment in the azimuth direction and about a horizontal axis for elevation alignment.

Two types of energy transport (thermal and/or electrical) can be used in dish systems, depending on the output of the plant. Thermal transport piping networks carry hot fluid directly from the receivers of a field of dish collectors to the end point of use (Reference 5). The collected heat energy can be used to power a central generator installed on the ground or it can be piped to a nearby industrial plant for a variety of process heat applications. Electrical energy is transported from a dish-electric module's engine/alternator by a transport system that collects electrical energy and either feeds it directly into the utility grid or, in some cases, inverts the output from module rectifiers before feeding it into the grid. A cogenerating dish plant can make use of both types of transport, thus increasing the versatility of dish power systems.

The control system for a typical solar thermal power plant consists of the hardware, software, and facilities needed for operating and monitoring the entire power supply system. A central minicomputer or microprocessor performs the monitoring and control functions during start-up, shutdown, and operation under normal, intermittent, and emergency conditions (Reference 6). Completely autonomous operation is required to reduce operator costs to an acceptable level.

Studies of thermal storage for use with dish systems have centered on the concept of latent-heat buffer storage. Buffer storage provides a "buffer" between the variations in solar flux and the heat delivered by the receiver to the engine, thus reducing the amount of time that the engine must operate under part-load conditions and thereby improving engine efficiency and extending engine life (Reference 7). This type of storage is integrated with the receiver and mounted at the concentrator focal plane. Longer-term storage for dish systems includes consideration of ground-mounted batteries (electrochemical), thermal storage using large external tanks, and thermochemical transport and storage.

SECTION II

COMPONENT DEVELOPMENT STATUS

A. CONCENTRATORS

1. Concentrator Characteristics

The concentrator is the largest and most costly component of a parabolic dish module. Selection of optical configuration, material, and structure for any particular concentrator design is based upon considerations of good optical efficiency and ultimately of low installed cost and low lifetime cost (Reference 8).

Two-axis tracking collectors can utilize concentrator configurations ranging from the conventional rigid paraboloidal mirror to the Fresnel or Cassegrainian (Figure 2-1). The paraboloidal shape may be segmented into a number of individual facets. However, there is no need to maintain an overall paraboloidal shape if small facets are properly oriented. For example, many spherical or flat facets can be placed on a flat support to form a Fresnel mirror. Other variations include Fresnel lens concentrators that allow the receiver to be closer to the ground and secondary concentrators that fold the optical path or increase the concentration of the collector. (A discussion of secondary and compound concentrators for dish systems is contained in Reference 9.)

The standard optical material for solar thermal concentrators is second-surface silver on glass, which is durable, highly reflective, but also relatively expensive, heavy, and fragile. Thin, low-iron glass is favored for this application because regular glass, which protects the reflective surface, also contributes to optical losses by absorbing part of the energy. The use of polymeric films is also being assessed. Polymers are attractive because of their low initial cost and may be first surface, second-surface, coated, or have the reflecting surface sandwiched between two other polymer layers (see Reference 8).

The concentrator reflector can be supported by either metal, cellular glass, reinforced polymeric material, or wood that is in turn supported by trusswork, stiffened by ribs, or sandwiched. In many cases, the reflector may be strong enough to support itself between the members of the structural framework; alternatively, it can be held in shape by tension and/or differential pressure.

2. Concentrator Optics

Mirror quality (i.e., surface accuracy and reflectance) is the primary contributor to optical efficiency. Even if a perfect paraboloidal-shaped surface were possible, the beam of energy concentrated upon the receiver aperture is always enlarged and weakened. Also, not all of the energy striking the surface of the mirror is reflected to the aperture; some is scattered and absorbed. Thus, the concentrator efficiency (i.e., the ratio of sunlight incident upon the concentrator to energy entering the

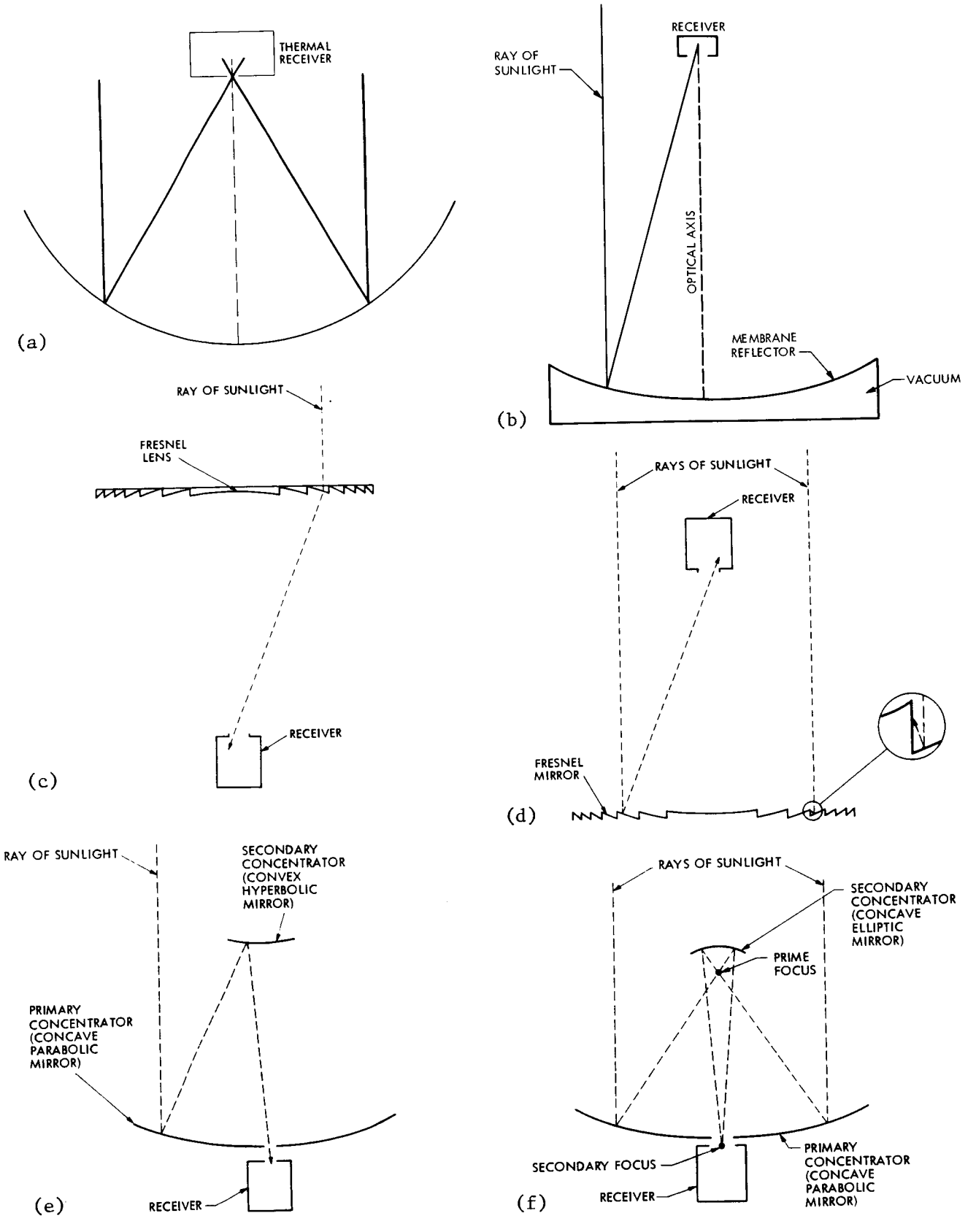

Figure 2-1. Concentrator Configurations (Reference 10): (a) rigid parabolic reflector; (b) pressure stabilized membrane reflector; (c) Fresnel lens concept; (d) Fresnel mirror concept; (e) Cassegrainian secondary configuration; (f) Gregorian secondary configuration.

receiver) will always be less than 100%. As mirror quality improves, so does the efficiency. Enlargement of the sun's image can be minimized by locating the receiver at a position corresponding to an f/D ratio (the ratio of the focal length, f, and the diameter of the concentrator's aperture, D) of about 0.6 (Figure 2-2 and Reference 11). Adding to beam enlargement is the fact that not all the energy is reflected in accordance with idealized optical surfaces. Instead, there is an angle of spreading that varies with different reflector materials. Plastic films have a large spreading angle; glass, a small one. The optical efficiency increases as the spreading angle decreases. Pointing errors resulting from inaccurate sun tracking and misalignment also can contribute to a reduction in collectable energy.

It is true that the highest performance concentrator has the highest quality surface. However, the optimal concentrator design must also consider cost, including that of the surface, substrate, and structure. A poorer quality concentrator having a lower cost might be preferred for certain applications, especially those requiring receiver operating temperatures in the low to medium ranges. In other words, it is necessary to maximize the ratio of thermal energy into the receiver over cost (kWt/$), accounting for reradiation and convection losses.

A method for evaluating reflective surfaces of parabolic dish concentrators is an essential part of their development. Criteria for the evaluation of second-surface glass mirrors, aluminum, and metallized polymeric films are defined in Reference 12.

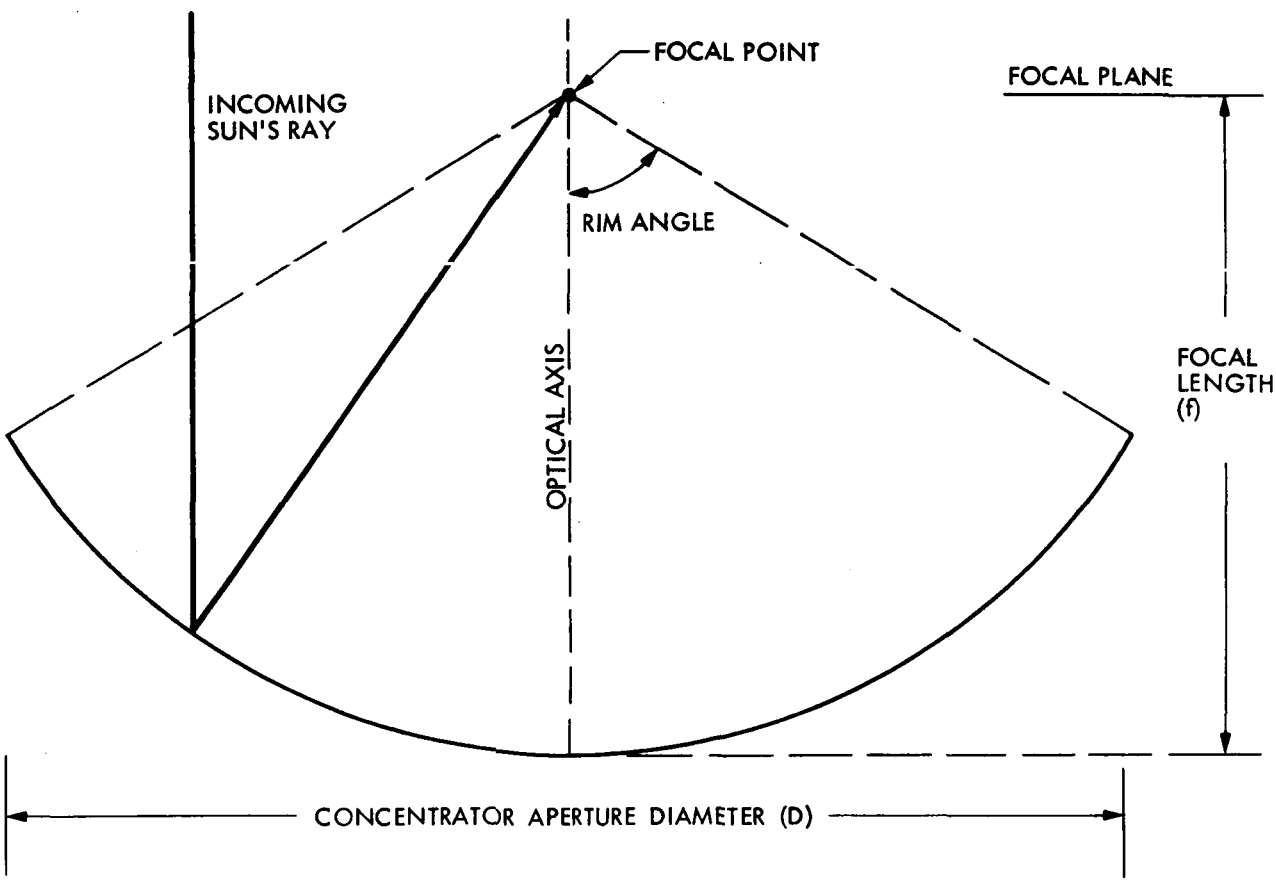

Figure 2-2. Concentrator Optics (see Reference 11)

3. Development Strategy

As shown in Table 2-1, ten types of concentrators have been designed, built, and/or tested under the DOE Solar Thermal Program. These concentrators are being developed for three basic applications: industrial process heat (IPH), cogeneration (total energy), and dish-electric power plants. During the late 1970s, the JPL TPS Project and Sandia National Laboratories, Albuquerque (SNLA) were both involved in developing first-generation thermal dish modules operating in the mid-temperature range (315 to 400°C, 600 to 750°F) for IPH and cogeneration applications. Four concentrators tested under the program were built by General Electric (the type used at Shenandoah), Omnium-G, Power Kinetics, and Raytheon, and are compared in Table 2-1 and described in Section II.A.5. The thermal module work at JPL was transferred to SNLA during FY 1982.

From its inception, the TPS Project has been concerned primarily with the evolution of components and modules that are autonomous electricity-producing units employing dish collectors coupled to high-efficiency heat engines. Efficient concentrators, supplying highly concentrated energy to receivers and engines, are required for such modules. Fabrication of the durable, high-efficiency test bed concentrators (by E-Systems) as vehicles for testing receivers and engines was a major step toward achieving the Project's goal as well as providing valuable data on concentrator materials, fabrication, and characterization (see Table 2-1 and Section II.A.4.a).

As a result of the Project's first competitive solicitation, three preliminary designs of first-generation concentrators were completed. They are described briefly below and detailed further in Sections II.A.4.b and c.

(1) A General Electric Company (GE) design, a rigid paraboloid with aluminized polyester (plastic) film on injection molded plastic reflective panels, was to emphasize low-cost materials and fabrication techniques. A prototype (PDC-1) was installed at the Parabolic Dish Test Site (PDTS) and was tested for optical performance.

(2) An original Acurex concept evolved into a more advanced concentrator composed of cellular glass gores with a second-surface silver/glass reflector. Development of this lightweight, self-supporting panel (gore) aimed at producing not only a lower-cost concentrator (PDC-2, being paired with an organic Rankine-cycle engine/receiver for the Small Community Experiment described in Section III), but also advanced techniques that could be used in the fabrication of second-generation concentrators.

(3) The Boeing membrane film reflector with protective enclosure was not carried past conceptual design until the Solar Energy Research Institute (SERI) began research and advanced development of polymers for mirrors and mirror enclosures in the early 1980s. SERI's work on this concept is described in Reference 3.

Table 2-1. Concentrator Configurations

Design Contractor	Optical Configuration	Optical Material	Mirror Support Structure	Mount	Foundation	Drive	Controls	Diameter, m	Focal Ratio, f/D	Optical Efficiency (Est.)	GCR[b] (Est.)
Acurex, PDC-2	Rigid parabolic (Fig. 2-1a)	Second-surface silver on glass	Cellular glass on ring truss	Elevation pivot on frame, which rotates in azimuth on concrete pier	Central concrete pier	El: electric motor/screw Az: electric motor	Microprocessor sun tracking	11 and 12	0.6	0.86	2000
Advanco	Rigid parabolic 8(Fig. 2-1a)	Second-surface silver on glass	Sheet metal racks on trusses	Off-horizontal bearing on tube for elevation and azimuth. Tube on horizontal bearing for more azimuth	Central concrete pier	Electric motor	Microprocessor sun tracking with data storage	11	0.6	0.89	2500
Boeing	Membrane (Fig. 2-1b)	Aluminized polyester film	Held by peripheral ring	Elevation trunnions on yoke, which pivots for azimuth. Enclosed in dome of polyvirylidine fluoride	Concrete pad	Electric motor	Microprocessor sun tracking with central computer	13	0.5	0.63	3200
E-Systems, TBC	Rigid parabolic (Fig. 2-1a)	Second-surface silver on glass	Cellular glass on trusses	Elevation trunnions on trussed pedestals that centrally pivot in azimuth with three wheels on track	Concrete pad	El: electric motor/screw Az: electric motor/wheel	Microprocessor sun tracking with ephemeris or stored data	11	0.6	0.89	1500 (Adjustable; 3000 max.
General Electric, Shenandoah	Rigid parabolic (Fig. 2-1a)	Aluminized acrylic film	Aluminum sheet on ribs, hub	Equatorial mount. Declination: pivoted to yoke, which is in hour angle bearings on tripod	Circumferential concrete piers	Electric motor/screw	Microprocessor analog sun tracking with ephemeris data with central computer	7	0.5	0.82	230

[a]See References 9 and 13.
[b]Geometric Concentration Ratio.

Table 2-1. (Cont'd)

Design Contractor	Optical Configuration	Optical Material	Mirror Support Structure	Mount	Foundation	Drive	Controls	Diameter, m	Focal Ratio, f/D	Optical Efficiency (Est.)	GCR[a] (Est.)
General Electric, PDC-1	Rigid parabolic (Fig. 2-1a)	Aluminized polyester film	Sandwich, wood core, polyester-glass face. Corrugated ribs sunward of mirror	Elevation trunnion at dish rim supported on base that pivots centrally with wheels on rail	Central and and circumferential concrete piers	Electric motor/cable	Microprocessor analog sun tracking with ephemeris data	12	0.5	0.70	1500
LaJet	Multiple membrane (Fig. 2-1b)	Aluminized polyester film	Peripheral rings on truss	Equatorial mount. Declination bearing on polar-axis tube, rotating in hour angle on cantilevered truss	Concrete piers	Decl: electric motor/actuator Hour angle: electric motor	Microprocessor sun tracking with stored data; membrane sensor for focus	9[b]	0.6	0.68	Variable
Omnium-G	Rigid parabolic (Fig. 2-1a)	Aluminum sheet	Polyurethane foam, metal trusses	Elevation central bearing on one pedestal, which is on a track for azimuth control	Concrete pad	El: electric motor/screw Az: electric motor/chain/friction	Analog sun tracking with clock	6	0.67	0.62	800
Power Kinetics, Inc.	Slats/Fresnel mirror (Fig. 2-1d)	Second-surface silver on glass	Polyurethane foam, metal frame	Elevation bearings in end plates, which are on framework on track that rotates in azimuth over fixed wheels	Steel frame on roof or circumferential concrete piers	El: electric motor/cable Az: electric motor/chain	Microprocessor analog sun tracking with stored data	9[c]	0.9	0.88	250
Raytheon	Rigid parabolic (Fig. 2-1a)	Second-surface silver on glass	Rings, trussed ribs, hub	Elevation bearing on post, which is on azimuth bearing on quadrapod	Concrete pad	El: electric motor/screw Az: electric motor/chain	Pointing by central computer from ephemeris data	7	0.45	0.89	125

[a]Geometric Concentration Ratio.
[b]Partly mirror.
[c]Square.

Two other concentrators by Advanco and LaJet were chosen because of their suitability for use in near-term Stirling and Brayton modules, respectively. They differ widely in materials and structure as shown in Table 2-1 and by the detailed descriptions given in Sections II.A.4.d and e. Both feature good optical and performance characteristics as well as low-cost fabrication techniques for planned mass production in the near future.

Other concentrator efforts managed by the TPS Project that are not described in detail herein include:

(1) Entech's (formerly E-Systems Energy Technology Center) preliminary design and optical (lens panel) testing of a Fresnel lens concentrator (see O'Neill, M. J., "A Transmittance-Optimized, Point-Focus Fresnel Lens Solar Concentrator," Proceedings Fifth Parabolic Dish Solar Thermal Power Program Annual Review, JPL Publication 84-13, DOE/JPL-1060-69, March 1, 1984).

A 14-m-diameter dome lens concentrator based upon this Fresnel lens concept will be fabricated and installed by Entech within the next 2 years in Albuquerque, New Mexico, as part of the DOE Innovative Concentrator Program managed by SNLA.[4]

(2) University of Arizona's concept definition of a Fresnel mirror concentrator.

(3) Boeing's design and optical (panel) testing of a rigid parabolic concentrator (see A Conceptual Design Study of Point Focusing Thin-Film Solar Concentrators, Final Report, prepared for Jet Propulsion Laboratory under Contract 955804 by Boeing Engineering and Construction, Seattle, Washington, November 11, 1981).

(4) University of Chicago's fabrication and testing of several secondary (trumpet-type) concentrators at the PDTS (see Winston, R., and O'Gallagher, J., "Non-Imaging Secondary Concentrators," Proceedings Fourth Parabolic Dish Solar Thermal Power Program Review, JPL Publication 83-2, DOE/JPL-1060-58, pp. 221-233, February 1, 1983).

4. Development of Candidate Concepts

During 1977 and 1978, the JPL Solar Thermal Power Systems Project evaluated proposals for low-cost, efficient parabolic dish concentrators (PDCs) capable of producing temperatures in the range of 540 to 815°C (1000 to 1500°F). The Project's selection of candidate concepts was based on the idea that first-generation hardware development would emphasize proven technology and techniques. This philosophy is seen in the first two concentrators developed by the Project: a test bed concentrator based on a microwave antenna design and a concentrator to be fabricated by an injection molding process used in the production of many commercial products.

[4]Personal communication, Mark O'Neill, Entech, Inc., P.O. Box 612246, DFW Airport, Texas 75261, May 15, 1985.

a. Test Bed Concentrator (TBC). In December 1977, a Request for Proposal (RFP) was released for design of a test bed concentrator that would (1) accommodate JPL-developed mirror facets, (2) provide solar tracking, and (3) support an engine/receiver unit at the dish focal plane for testing purposes. On September 14, 1978, a contract was awarded to E-Systems of Dallas, Texas, for the fabrication of two such concentrators (Reference 14).

TBC Structural Characteristics. The TBC structure met design specifications for stiffness and accurate pointing capability by using proven satellite communications antenna technology. The reflector structure of a 13-m-diameter communication antenna was adapted for this application with a pedestal modification that would enable full sky coverage. Key design requirements of the TBC are listed in Table 2-2.

The reflector support structure is a steel space frame consisting of eight truss beams radiating from a central hub and interconnected with diagonal and intercostal members (Reference 15). The hub, which is unchanged from the 13-m antenna configuration, provides exceptionally high stiffness. The receiver support structure is a tubular bipod connected to a receiver ring and stabilized laterally and torsionally by adjustable rods attached to the dish periphery. The pedestal is an elevation over azimuth mount with a wheel and track alidade. For azimuth tracking, a 3-hp dc servo motor drives one of the three alidade wheels through a 740:1 gear reducer; in elevation, an identical motor drives a 20-ton screw-type linear actuator through a single helical gear box. The control system provides for active sun tracking (via two photocell sensors) in addition to program tracking (using a microprocessor).

Mirror Facet Development. After reevaluation of earlier work in the areas of material selection, environmental test, optical characteristics, and reliability, Foamglas (a soda-lime cellular glass insulating material that is lightweight, easily shaped, and durable) was selected as the mirror substrate. Subsequently, block size and mirror material had to be determined in light of the TBC application and the structural characteristics of Foamglas. Analysis showed that block sizes greater than 46 cm (18 in.) square would provide satisfactory performance. An actual block size of 61 x 71 x 5.1 cm (24 x 28 x 2 in.) was chosen, meaning that 224 facets would be required to compose the 11-m-diameter concentrator. Several materials were then analyzed as candidates for the mirrors, mirror adhesive, and sealant coatings for the mirror/substrate interface; those materials ultimately selected for mirror fabrication are listed in Table 2-3. Prior to assembly at JPL, the optical characteristics of each facet were measured in the laboratory using an optical tunnel, a reflectometer, and a photometer (Reference 16). A finished TBC mirror facet is shown in Figure 2-3.

Assembly and Installation. Trial assembly of the reflector structures and pedestals at the fabricator's facility ensured their timely installation at the Parabolic Dish Test Site (PDTS). Installation and operational checkout was completed in October 1979, 2 months after ground breaking for the foundations. Attachment of the mirror facets was done by fastening three flexure tabs (bonded to the facet substrate) to the reflector

Table 2-2. TBC Key Design Requirements (see References 15 and 17)

Item	Design Requirement
Physical	
Aperture diameter	11 m (35 ft)
Rim angle	45°
Focal ratio, f/D	0.6
Focal point load	504.4 kg (1100 lb)
Receiver mounting	76 cm (30 in.) inside diameter ring
Tracking control	
Azimuth	
Travel	±178°
Slew rate (13 m/s wind)	2028°/h
Elevation	
Travel	0 to 90°
Slew rate (27 m/s wind)	168°/h
Tracking accuracy (operating wind)	0.05°
Pointing accuracy	1.0°
Environmental	
Operating wind	13 m/s (30 mi/h) gusting
Survival wind	45 m/s (100 mi/h)
Seismic	0.25 G, any direction
Ice	0.4 cm (1 in.) radial
Snow	0.4 kg/m^2 (10 lb/ft^2)
Reflector	
Nominal diameter	11 m
Output	70 kWt at 800 W/m^2 insolation
Mirror facets	
Number	224
Material	Second-surface glass
Nominal size	60.96 x 71.12 cm (24 x 28 in.)
Nominal radii of curvature-Three regions	1320, 1574.8, 1610.4 cm (520, 620, 634 in.)
Initial reflectance	95% maximum
Slope error	1 mrad
Focal length	6.6 m (21.65 ft)

Table 2-3. Materials Selected for TBC Mirror Fabrication (see Reference 16)

Item	Material (Manufacturer)
Substrate	61 x 71 x 5.1 cm (24 x 28 x 2 in.) Foamglas High Load Bearing 136.17 kg/m^3 8.5 lbs/ft^3 density) (Pittsburgh Corning)
Mirror	60 x 70 x 0.15 cm (23-3/4 x 27-3/4 x 0.058 in.) Corning Glass Code 0317 (Silvered by Falconer)
Mirror adhesive	DER 332 - Dow Epoxy Resin 9427 Hardener (Furane Plastics)
Support tabs	0.032 Aluminum with 5.1 x 7.6 cm (2 x 3 in.) contact area with Foamglas
Support tab adhesive	PC-88 two-part adhesive (Pittsburgh Corning)
Mirror edge seal	Vulkem 116 Urethane Sealant (Nameco)
Foamglas sealant	Pittcote 404 Acrylic Latex (Pittsburgh Corning)
Paint	Chemglaze II A276 White Polyurethane

structure while it was still on the ground. The entire structure was then placed on the pedestal in a single lift by a 45-ton hydraulic crane (see Reference 15).

TBC Characterization. The TBC mirror facets were aligned at night using a semi-distant incandescent light source to produce a reflected image on the focal point target, which was marked with a series of concentric rings 2.54 cm (1 in.) apart (Reference 18). Because only one mirror facet could be aligned at a time, covers for individual mirrors were fabricated, with Velcro fasteners for easy removal and reattachment to the mirrors. The TBC was boresighted to the aimed light source using two sets of cross hairs and two aperture disks that were replaced by disks with successively smaller apertures. Individual mirror alignment was physically accomplished by adjusting the three flexure tabs that attach the facet to the reflector structure.

The TBCs were then characterized using a flux mapper (Figure 2-4) and a cold-water calorimeter. The flux mapper uses a Kendall radiometer as the sensing device and is mounted on an x-y-z motor-driven positioning mechanism for testing. Results of flux mapper testing show that a TBC can produce a peak flux of 1750 W/cm^2 at a normalized insolation of 1000 W/m^2 within a 20.3-cm (8-in.)-diameter aperture, resulting in temperatures up to 3300°C (6000°F). Cold-water calorimeter testing has shown that the TBCs can each

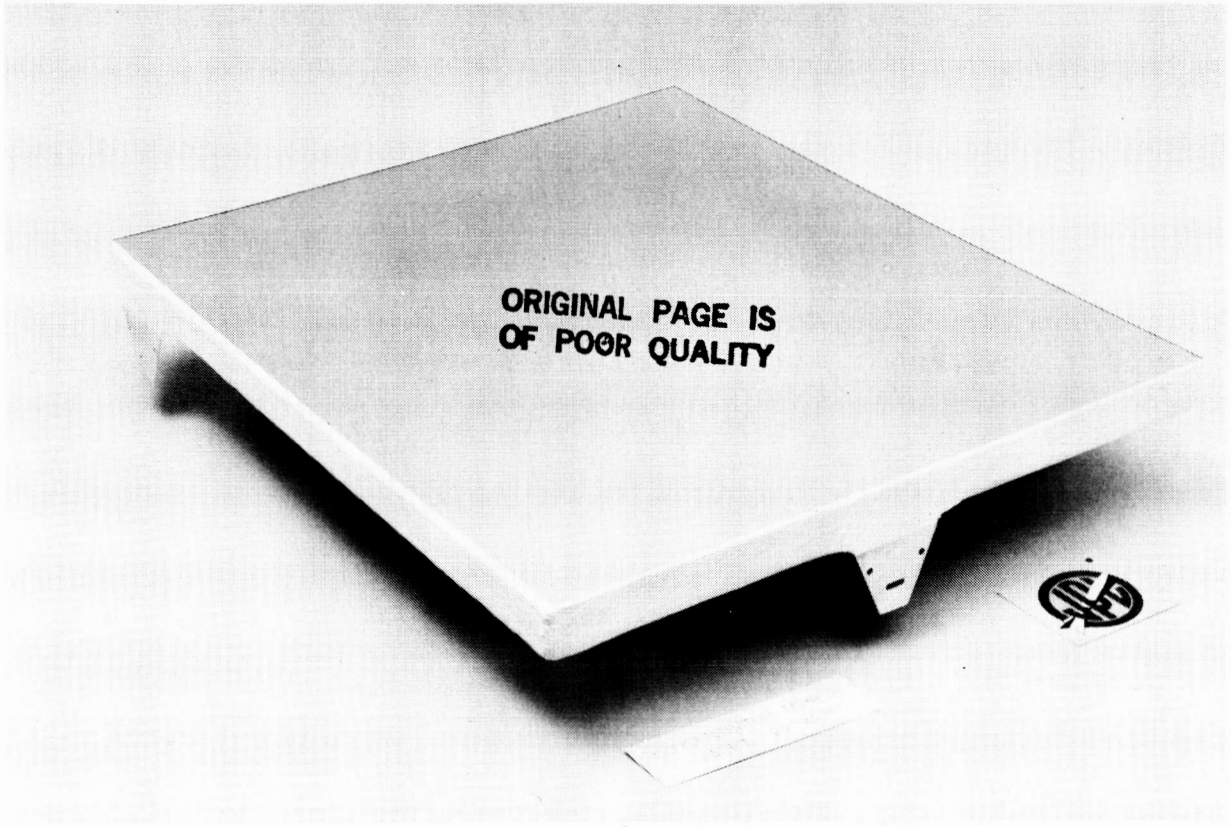

Figure 2-3. TBC Mirror Facet

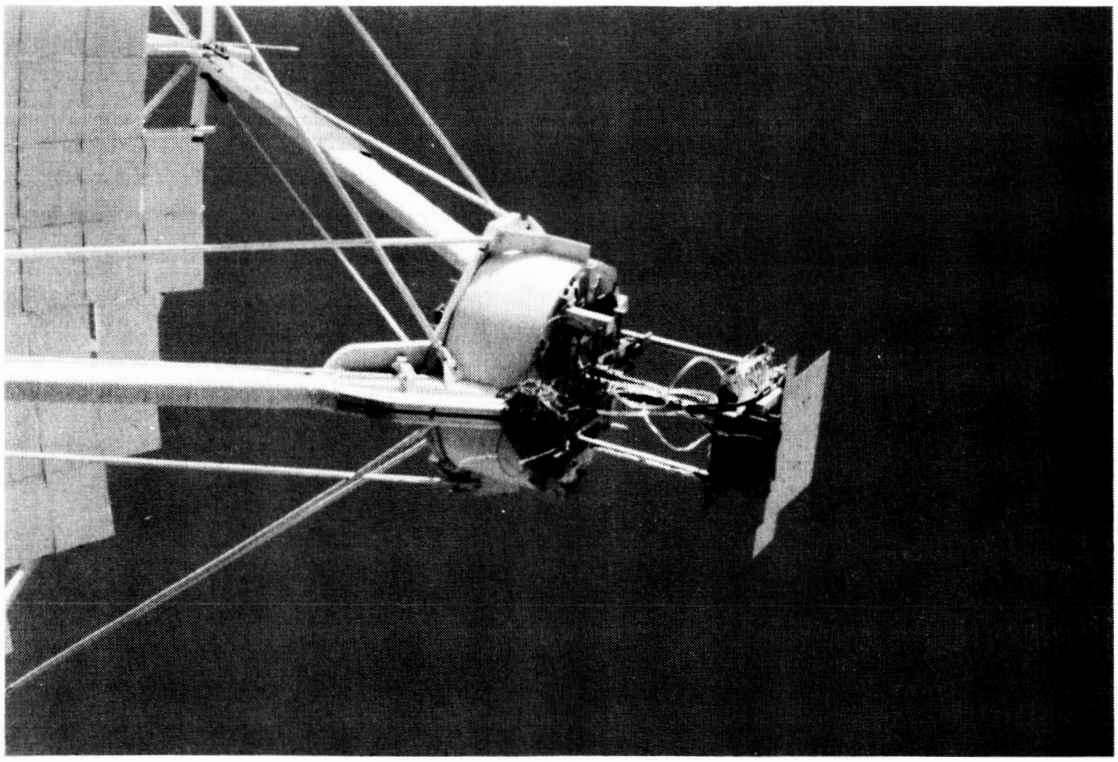

Figure 2-4. Close-up of Flux Mapper from Outer End

produce a maximum of 82 kWt at an insolation of 1000 W/m^2 within apertures of 56 cm (22 in.) and 25.4 cm (10 in.) in diameter (Reference 19). During component testing, temperature, thermal power level, and flux intensity distribution at the concentrator focal plane are routinely controlled by the number, location, and alignment of uncovered mirror facets (Reference 20).

Throughout many years of operation at the PDTS, the test bed concentrators (Figure 2-5) have proven to be valuable vehicles for testing numerous kinds of receivers and power conversion units (see Sections II.B and C of this report). In 1984, both test bed concentrators were disassembled and reinstalled at the Sandia National Laboratories test facility in Albuquerque, New Mexico, where they will be used to test advanced parabolic dish-electric subsystems.

b. Parabolic Dish Concentrator No. 1 (PDC-1). The fabrication of PDC-1 was the culmination of TPS Project efforts to develop a first-generation low-cost concentrator. Preliminary design contracts were awarded to Acurex Corporation, The Boeing Company, and General Electric Company (GE). These designs were completed in March 1979. The Acurex design was based on a faceted, "compressed" paraboloidal (Fresnel) reflector made up of 33 triangular facets mounted independently on a flat triangular frame (see Reference 17). The Boeing design featured an inflated plastic enclosure to protect collector components from all environmental loads, thus permitting the use of lightweight, less expensive internal structures. The reflector for this design was to be a 13-m diameter, first-surface metallized plastic film membrane shaped by a slight vacuum within the frustrum (refer to Figure 2-1b and Reference 17). General Electric's design, featuring an 11-m-diameter reflector made of

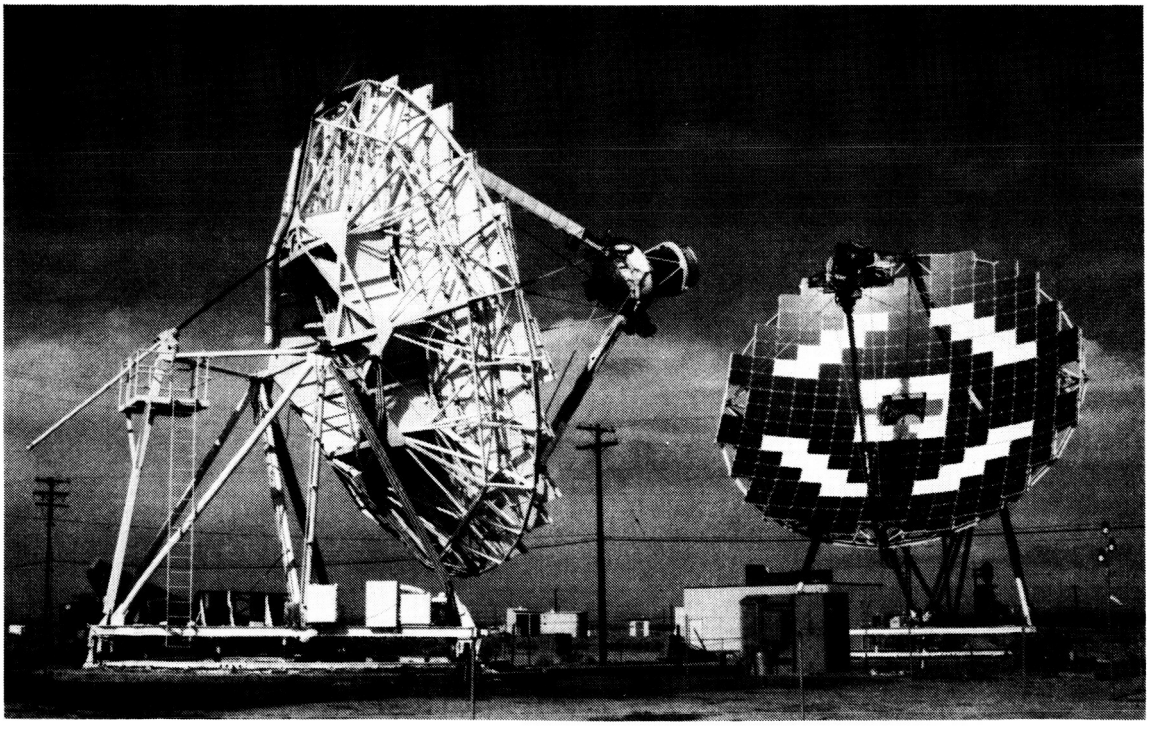

Figure 2-5. TBCs During Component Testing at the PDTS

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plastic injection molded panels, was selected for further development: In August 1979, GE was given a contract for detailed design of their concept, and in 1981 separate contracts were awarded for panel fabrication, structure fabrication and installation, and controls.

PDC-1 Design Characteristics. The detailed design of the General Electric concept (Figure 2-6), later known as Parabolic Dish Concentrator No. 1, was completed in mid-1981. For the purpose of engine compatibility, the concentrator diameter was increased from 11 m to 12 m in order to provide an output of 80 kWt for a receiver operating at 815°C at an insolation of 1000 W/m^2. It is composed of 12 radial gores, each comprising an inner, center, and outer panel. The 36 panels are attached along their radial edges to 12 radial steel ribs located in front of the reflective panels. The reflective surface is an aluminized plastic film (Llumar) laminated to a plastic sheet and then bonded to a molded fiberglass/balsa sandwich panel. The original injection molded plastic panel with integral ribs, which was proposed for this concentrator, was abandoned because of fabrication difficulties.

The elevation-over-azimuth mount uses a wheel and track arrangement with outboard trunnions to permit stowing in a face-down position and access to the engine/receiver unit. The control system, which includes a central computer, manual control panel, and sun sensor, enables the concentrator to track the sun by first pointing it to a predetermined position calculated from the solar ephemeris. When the concentrator is about 1 deg from the sun's position, the sun sensor assumes control and maintains alignment of the solar image with the receiver aperture.

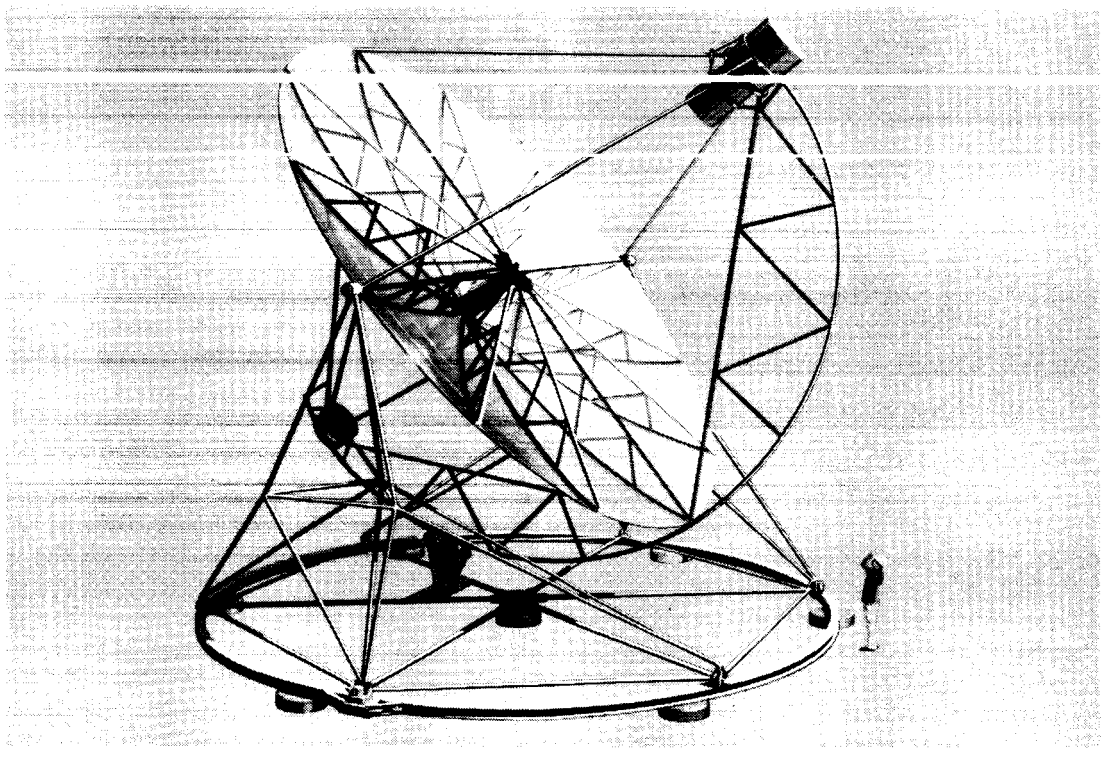

Figure 2-6. General Electric Concept for a First-Generation Concentrator

Panel Fabrication and Testing. Under a separate procurement, Design Evolution 4 began fabrication of the PDC-1 panels in 1981. In their specialized molding facility in Lebanon, Ohio, they used three separate tooling masters made by System Resources to mold the inner, center, and outer panels. The molding facility's press platten, 7 by 11.5 ft long, is one of the largest resin transfer presses in the United States. It is raised by six air bags to provide a clamping force of 180 tons. Each panel substrate was fabricated by loading the mold bottom half with a mat of continuous strand glass fibers, a layer of end grain balsa blocks, and another fiberglass mat. The mold was then closed and injected with polyester resin, which flowed throughout the cavity and filled the glass fiber mats and all gaps between the balsa blocks. The reflective film laminate was bonded to the panel with contact cement (Reference 21).

The first set of Design Evolution 4 panels was optically tested in the JPL 25-ft Space Simulator (Figure 2-7). This facility allows use of a single zenon arc lamp that provides a high quality collimated beam of light over a circular area of almost 6 m (19.7 ft) in diameter. This beam was used to measure directly the optical forming characteristics of the panels. Test results indicated that, although the performance of a concentrator assembled from these panels would be satisfactory, it could be increased by improvements in panel manufacturing techniques and the use of higher quality optical materials. (Further description of optical testing in this facility is presented in Reference 22.)

Structure Fabrication and Installation. In the spring of 1982, site preparation for the installation of PDC-1 at the PDTS was carried out by Ashland Construction simultaneously with fabrication of the structure by Alco Machine Company of Birmingham, Alabama, for Ford Aerospace and Communications Corporation (FACC), the prime contractor. After curing of the concrete foundation, Valley Iron installed the track, erected the mount frame, and began assembly of the dish structure. A trial of the latter had been performed at the Alco factory prior to installation. The 36 reflective panels were installed after individual optical testing using a new attachment scheme to accommodate large shear loads. Delamination of some of the reflective sheet during and after installation led to the consideration of an anaerobic contact cement for future panels (Reference 23). Subsequent dish rework included reinstallation of the panels, which was warranted after initial optical testing of the assembled concentrator (discussed below). The panels were reinstalled by redrilling rib attachment holes while each panel was held in the proper parabolic contour under close temperature conditions. These rework efforts resulted in a threefold reduction in the focal spot diameter (see Reference 23). The completed concentrator is shown erected at the PDTS in Figure 2-8.

Control System. The control system for PDC-1 as used at the PDTS employed sun sensors for primary control and a computed sun ephemeris for simultaneous check and cloud passage. Tracking action was a discontinuous, stop/start motion, and operation was at a 0.05-deg deadband for optical characterization. The control system performed well for the brief period before PDC-1 was moved to SNLA. A detailed description of the system, including message exchange protocol and basic microprocessor control logic, is contained in Reference 24.

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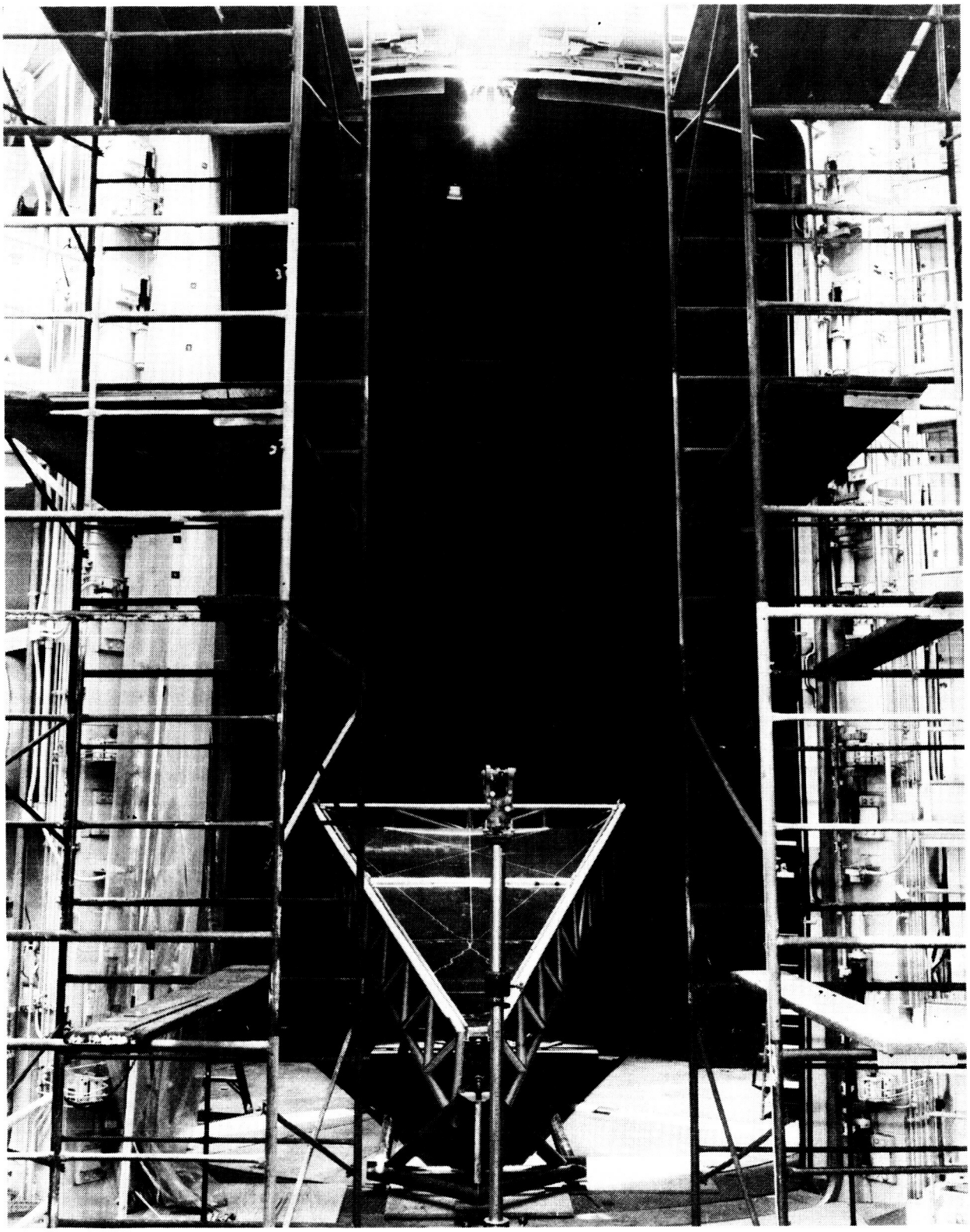

Figure 2-7. PDC-1 Concentrator Panel During Testing in the JPL 25-ft Space Simulator

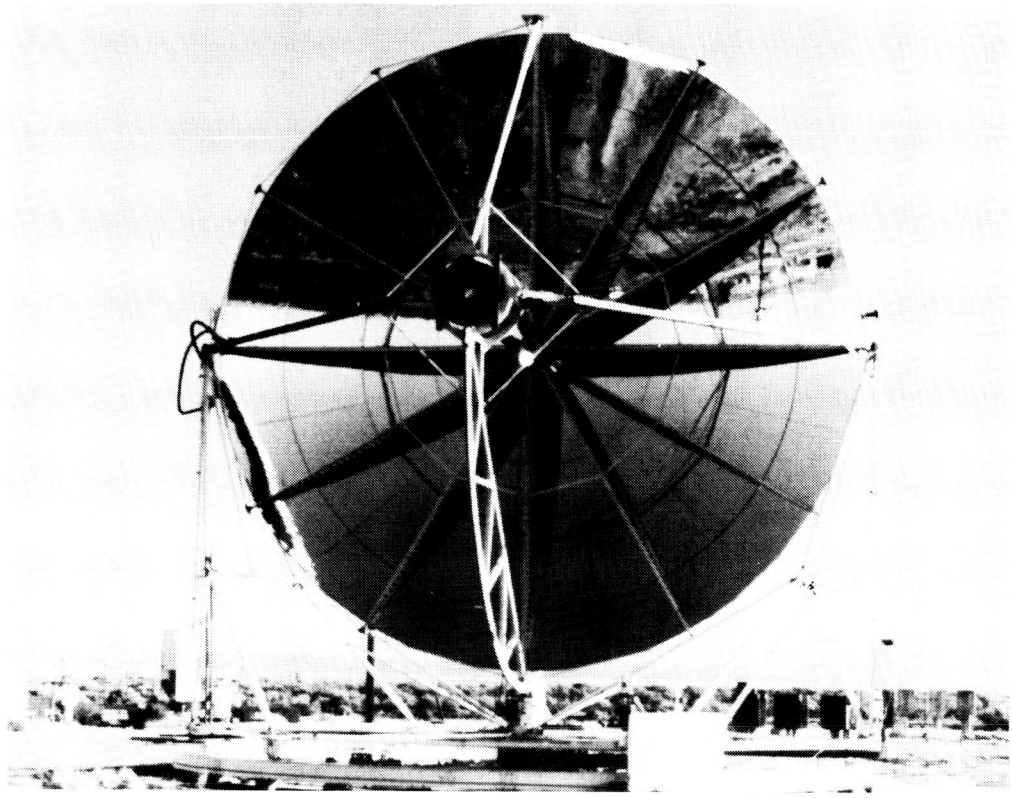

Figure 2-8. PDC-1 at the Parabolic Dish Test Site

Optical Testing. Tests for optical accuracy of the fully assembled PDC-1 were conducted during October and November 1982. The results of these tests were used for evaluating the performance of the concentrator and were instrumental in the development of a succcessful panel installation procedure as mentioned above.

Two diagnostic techniques were used to determine the relationship between the image quality and the mechanical properties of the reflecting surface. A photo-detector raster scan was used to determine the intercept factor distribution, and various image photography techniques were used with a point-source configuration to predict the intensity distribution of the concentrator when it is pointed at the sun. A diagnostic picture taken through a telescope at a distance of 600 to 900 m (2000 to 3000 ft) is shown in Figure 2-9. The intercept factor distribution and the diagnostic pictures indicate that PDC-1 will perform satisfactorily when coupled to a suitable power conversion unit (References 25 and 26).

c. Parabolic Dish Concentrator No. 2 (PDC-2)

Background and Preliminary Design. After reevaluation of the low-cost concentrator design proposed by Acurex in March 1979 (discussed previously), an alternate concept based on the Acurex advanced cone design was selected for development as a backup for PDC-1. The processes used to design and fabricate this 11-m-diameter, single-pedestal-mounted concentrator also were planned for use in second-generation concentrators (Reference 27).

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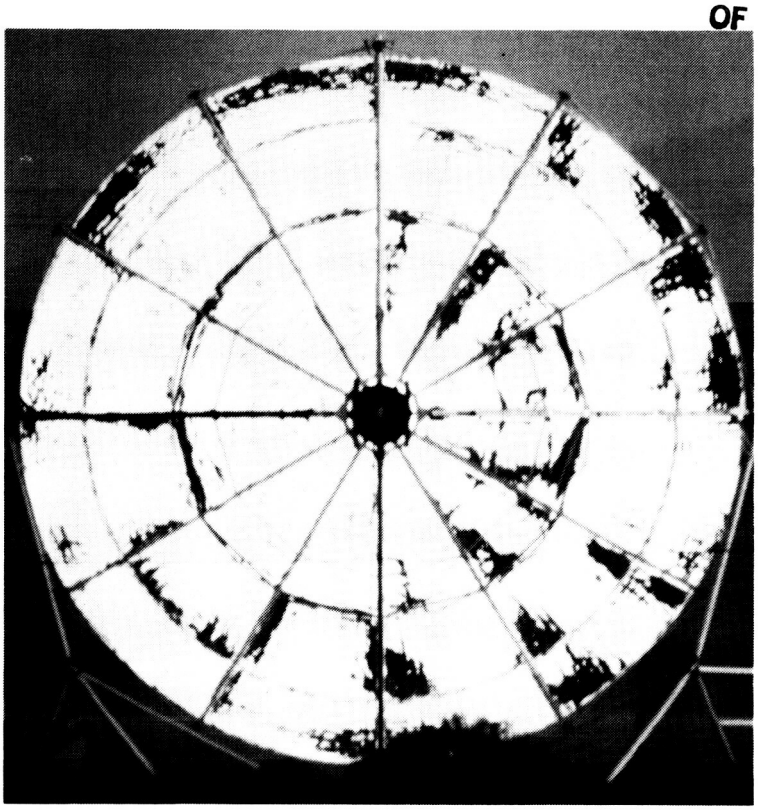

Figure 2-9. Diagnostic Photograph of PDC-1. (The white areas indicate panel regions forming images within a 15-cm-diameter circle.)

During 1979 and 1980, Acurex was under contract to JPL to complete tasks relating to their concentrator concept: (1) preliminary design of a cellular-glass-substrate advanced solar concentrator, (2) detailed design of reflector gore panel, and (3) a mass production cost estimate (Reference 28). The rationale for this design is that a lightweight, self-supporting panel will decrease drive and foundation loads and reduce installation labor -- all leading to lower cost. Cellular glass is relatively inexpensive and also durable, has a high stiffness-to-weight ratio, and matches the thermal expansion properties of glass.

PDC-2 was designed as a two-axis tracking parabolic dish, 11 m in diameter, consisting of 24 inner and 40 outer gores attached at three points to a steel ring truss support structure (Figure 2-10) The gores act as cantilevered beams supporting the reflective surface, which is made of back-silvered, low-iron, soda-lime glass drawn to a thickness of 0.7 mm (0.028 in.) then bonded and shaped to the cellular glass substrate using a pressure-forming technique. The concentrator output was projected to be 79 kWt through a 24-cm (9.4 in.) aperture to produce receiver operating temperatures up to 925°C (1700°F) at an insolation of 1000 W/m^2.

Gore Fabrication and Testing. On March 30, 1981, Acurex delivered seven paraboloidal reflective panels to JPL for optical testing. Six of the gores were the cellular-glass type (Figures 2-11 and 2-12) consisting of (1) a contoured cellular glass core with a paraboloidal front surface and spar-stiffened rear surface, (2) a large full-surface facet of

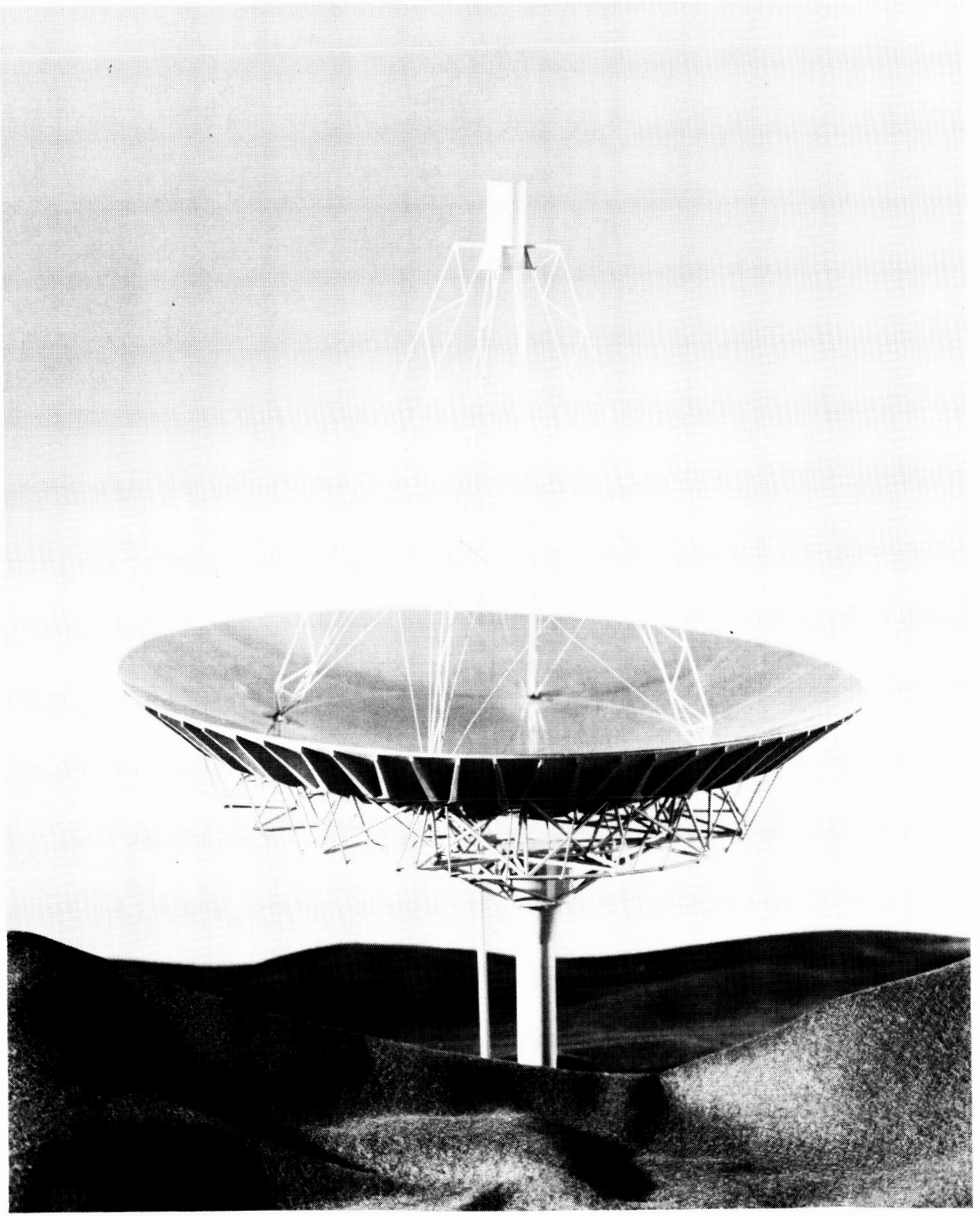

Figure 2-10. Model of Acurex Advanced Concentrator Design (PDC-2)

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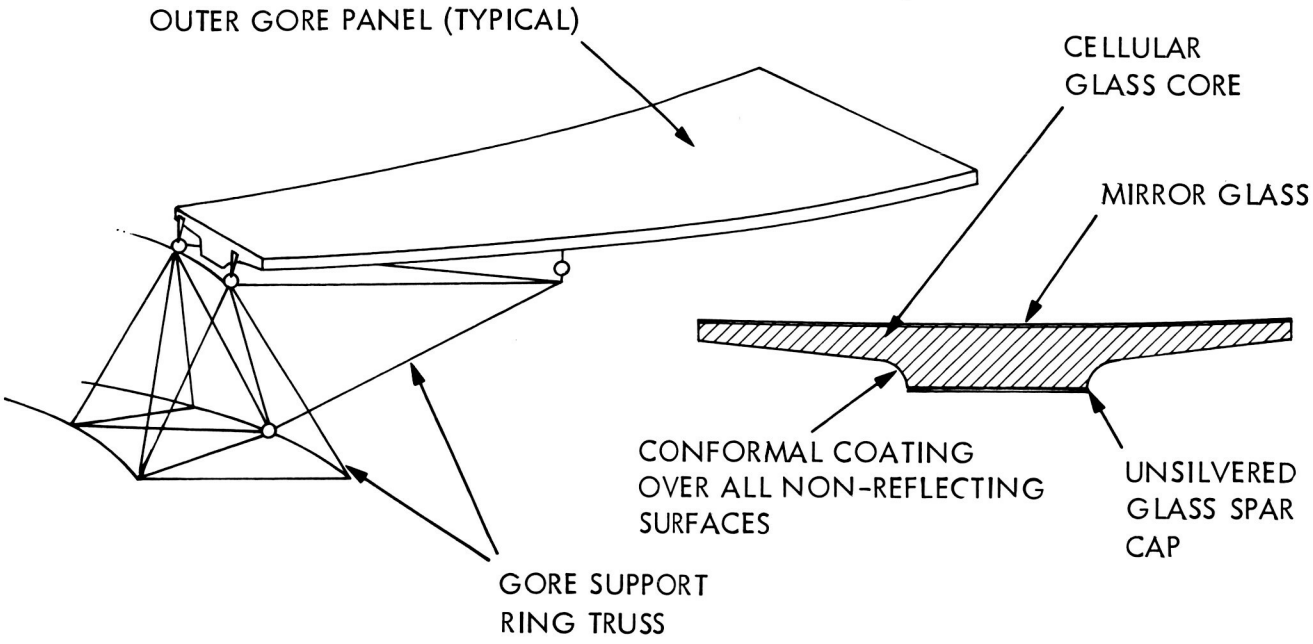

Figure 2-11. Cross-Sectional Diagram of Acurex Concentrator Gore

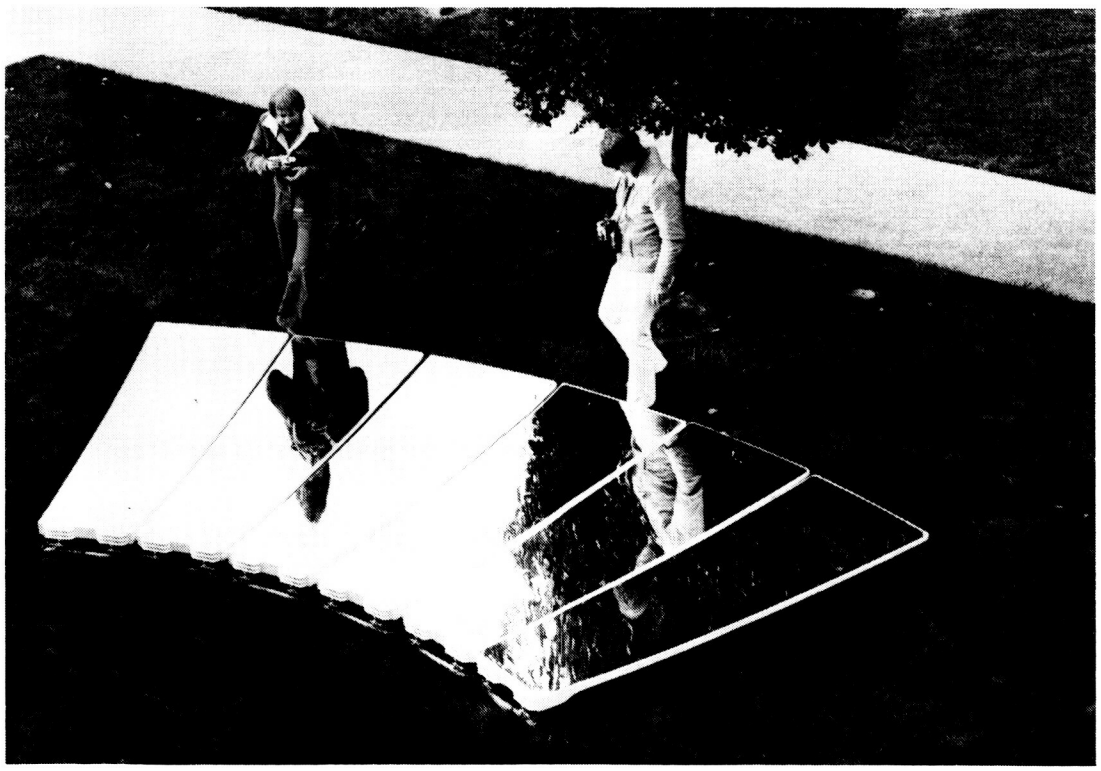

Figure 2-12. Acurex Cellular-Glass-Type Gores Delivered to JPL

flexed back-silvered glass mirror bonded to the paraboloidal front surface, and (3) a full-length structural glass cap bonded to the spar on the rear surface. The cellular glass core is protected by a coating of butyl rubber that forms an edge seal around the mirrored face of the gore to prevent moisture damage to the reflective silver coating. White silicone/alkyd paint shields the butyl rubber from ultraviolet radiation. During laboratory testing, these cellular glass gores showed excellent optical quality (see Reference 27).

The seventh panel delivered to JPL is a glass-reinforced developmental panel. Initial optical tests indicated structural problems, the resolution of which would require additional development (Reference 29).

Future Plans. A later version of PDC-2, intended for use in the Small Community Solar Thermal Power Experiment (see Section III), employs a 12.2-m-diameter dish. The concentrator was modified to increase the power delivered to the receiver to 95 kWt for use with the proposed Barber-Nichols 25-kWe organic Rankine-cycle power conversion assembly mated to the 15-in.-diameter aperture FACC receiver. Construction of the 12.2-m PDC-2 was initiated, then suspended when DOE and FACC were unable to finalize contract terms.

d. Advanco Concentrator. An 11-m-diameter concentrator was developed and fabricated by Advanco Corporation as part of the Stirling module development program at JPL (see Section III). This concentrator is made up of 320 facets, each 460 x 610 mm (18 x 24 in.). The individual facets are foamglass-backed thin glass, back-silvered mirrors providing a total reflective surface area of 89.2 m^2 (960 ft^2) for the concentrator. The mirror facets are attached to flat racks that are in turn attached to a carbon steel truss structure with leveling attachments that allow the reflective surface to approximate a paraboloid (Figure 2-13).

The truss is mounted on a pedestal via an exocentric gimbal mechanism (developed by Rockwell International), which supports the concentrator reflector. The pedestal, which is 750-mm (30-in.) carbon steel pipe in a poured concrete footing, has an upper joint (elbow) and a lower joint (shoulder). The elbow joint consists of a turntable bearing that is rotated using a pinion gear, gear reduction, and a small electric motor. This rotation (about an axis through the center of mass) reduces torque requirements and produces elevation and some azimuth drive. The shoulder joint pivots and produces azimuth drive only (see Reference 11). Concentrator control is accomplished with an Electrospace Model 93C-15 antenna controller and motors (Reference 30).

e. LaJet Concentrator. In 1979, the LaJet Energy Company began developing concentrators with plans to market mass-producible collector units. Since that time, LaJet has fabricated concentrators using the same general configuration in progressively larger sizes: 18.81, 38, and 44 m^2 of reflective surface area. LaJet's 38-m^2 version is shown in Figure 2-14. Their 44-m^2 concentrator, the LEC 460, was planned for use in the Projects' Brayton module development program (see Section III).

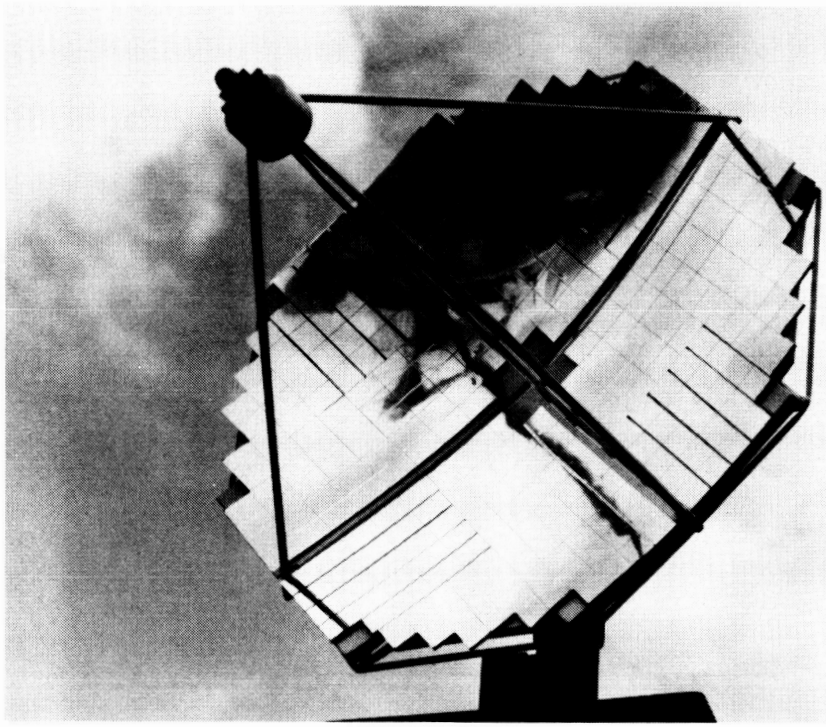

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Figure 2-13. Model of Advanco Concentrator

Description. The LEC 460 features an open lattice space frame, a cantilever truss, and multiple low-cost circular-dish reflectors. The open lattice structure is made of lightweight round steel tubing connected with specially designed joints that are bolted together with simple fittings. The cantilevered design permits sun tracking and adjustments in elevation and azimuth via small motors. Each 1.52-m (60-in.)-diameter mirror consists of a shallow, lightweight, cylindrical housing with a closed rigid back and an open top. A reflective thin film, which is easily replaceable, is attached to the top of the housing. A closed-loop, adjustable mechanism controls the partial vacuum forming the concave shape of each individual mirror facet (as in Figure 2-1b) and is used to achieve desired concentration ratios and focal lengths. The manufacturer-stated efficiency is approximately 70%.

Optical Testing of a Mirror Facet. In mid-1983, an LEC 460 concentrator facet was tested for imaging quality at JPL. The following two methods were used: (1) auto-focus tests with a point source of light at the facets' radius of curvature and (2) tests with the sun close to the horizon as a distant light source. The results of these tests indicated that all of the solar image reflected by an LEC 460 made of facets identical to the test specimen should fall within a 22.9-cm (9-in.)-diameter if the outer facets are carefully adjusted. Such a concentrator would provide acceptable performance.

These optical tests not only evaluated the imaging characteristics of a sample facet, but also demonstrated the kind of tests that can be conducted for quality control during facet manufacture and for characterizing a complete concentrator. (A detailed description of this testing procedure is contained in Reference 31.)

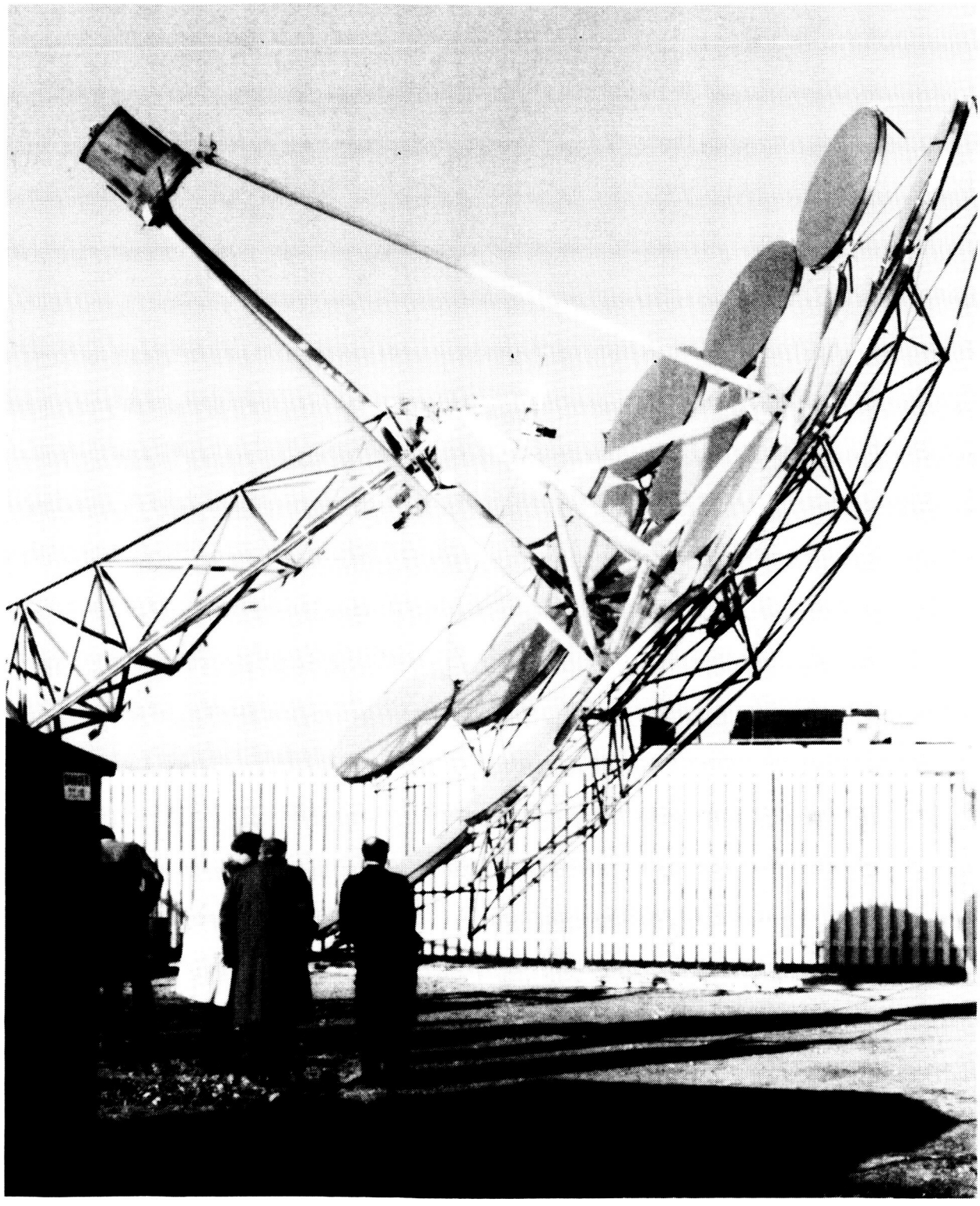

Figure 2-14. LaJet 38-m^2 Concentrator

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5. Other Concepts Tested under the DOE Solar Thermal Program

Four other concentrators were tested as part of the DOE Solar Thermal Technology Program. These four, manufactured by Raytheon, General Electric, Omnium-G, and Power Kinetics, Inc. (PKI), are shown in Figure 2-15 (a), (b), (c), and (d), respectively.

a. Raytheon and General Electric/Shenandoah. Sandia National Laboratories-Albuquerque (SNLA) began testing the Raytheon and General Electric/Shenandoah collectors (a concentrator plus a receiver) under a program to develop point-focusing concepts for lower temperature applications (315 to 400°C, about 600 to 750°F), e.g., irrigation or total energy (cogeneration) systems.

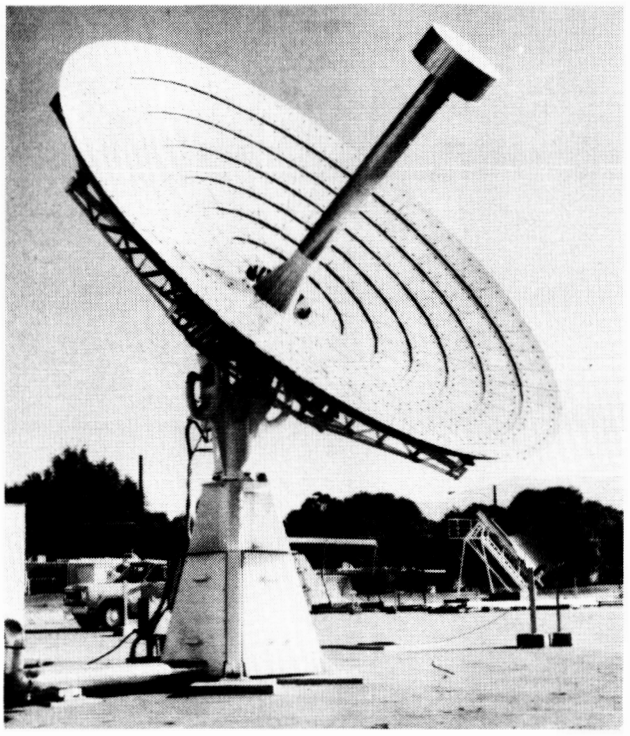
The Raytheon concentrator, 6.7 m in diameter, consists of spherical mirror segments (sagged, back-silvered, water-white crystal glass) that are hard mounted on an aluminum substructure. The collector tracks in azimuth and elevation by computer-controlled dc stepping motors (see Reference 9).

The General Electric/Shenandoah collector (so named for its use in the Solar Total Energy Project located in Shenandoah, Georgia) is 7 m in diameter having 21 panels, each made of aluminum sheet that is coated on one side with 3M's FEK-244 reflective film and die-stamped to the desired parabolic contour. The dish's central hub is supported by a concrete counter-weighted yoke structure that is held at an angle by two solar-axis bearings and supported by a tubular carbon steel tripod mount. Rotation of the yoke about its axis provides solar tracking (References 32 and 33).

b. Omnium-G. Omnium-G, a company that is no longer in business, built several collectors in 1978 and 1979 that were installed at various sites in the United States. Two such sites are the Southern New England Telephone Company (SNETCO) in Connecticut and JPL's Parabolic Dish Test Site (PDTS) in California. The 6-m reflector is polished aluminum sheet on polyurethane foam supported by trusses. The concentrator is rotated on a track by electric drive motors. Testing has shown the optical efficiency to be about 0.6 at a geometric concentration ratio of 800 (see Reference 9).

In 1980, in response to a DOE request that JPL monitor the Omnium-G SNETCO installation, the Omnium-G system at the PDTS was retrofitted to the latest configuration. In August 1981, the system (with a new tracking unit and elevation drive) operated reliably with no operator intervention during a normal diurnal cycle. Refocusing of the mirror petals and adding insulation to the steam lines improved its efficiency. Problems with installing the steam/generator proved to be so intractable that JPL shipped this component to SNETCO "as is" and subsequently dismantled and surplussed the PDTS Omnium-G system in 1984, without conducting further testing (Reference 34).

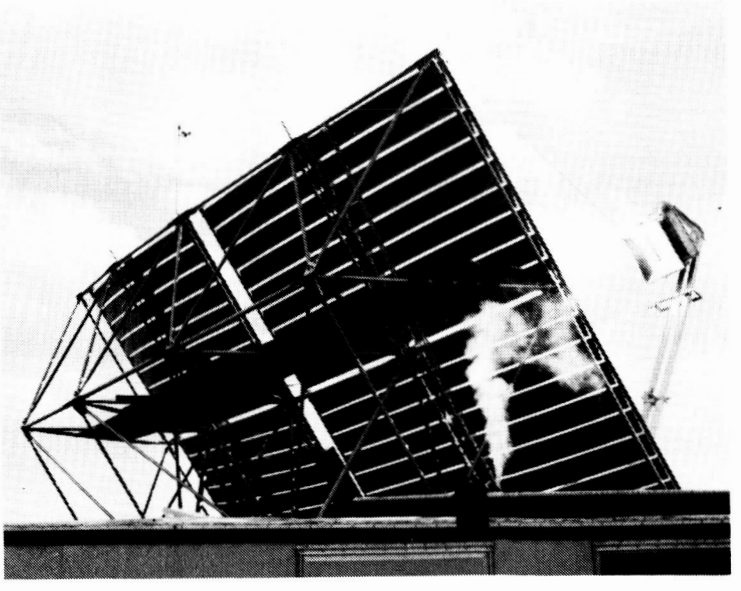
c. Power Kinetics, Inc. The PKI collector has 864 square mirrors (each 0.305 m^2, 1 ft^2) mounted on 108 identical curved modular support assemblies attached to a lightweight space frame that is in turn mounted on a steel track. Rotating the track on its casters provides for



(a) Raytheon

(b) General Electric

(c) Omnium-G



(d) Power Kinetics, Inc.

Figure 2-15. Other Concentrators Tested under the DOE Solar Thermal Program

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azimuth control; rotating each mirror support assembly around its center of gravity provides elevation adjustment. The concentrator focuses sunlight onto a cavity receiver producing steam for process heat applications.

A PKI collector is now in operation at the Capitol Concrete Products block plant in Topeka, Kansas. Conception and installation of this system experiment was carried out by Applied Concepts Corporation under the direction of the JPL TPS Project, who helped transfer management of the experiment's operational phase to SNLA in FY 1982. (Reference 35 contains information on that phase of the Capitol Concrete system experiment.) A second PKI collector bought by JPL was installed at Hill Air Force Base in Utah.

In 1984, a modification of the PKI collector was selected for use in the newly contracted Small Community Experiment at Osage City, Kansas.

Further information about the SNLA thermal dish program is contained in References 36, 37, and 38.

6. Concentrator Technology Assessment Summary

Concentrators designed, developed, and/or tested as part of the TPS Project included rigid parabolic, membrane (pressurized and/or multiple), Fresnel mirror or lens, and secondary. Initially, the rigid parabolic and Fresnel mirror concentrator concepts were defined by JPL and the University of Arizona, respectively. Preliminary designs were prepared by Entech (Fresnel lens) and Boeing (pressurized membrane). A Boeing design of a rigid parabolic concentrator included tests of a mirror segment; Acurex work on a rigid parabolic type included partial detailed design plus tests of several mirror panels. Four concentrators were designed, built, and tested: E-Systems/JPL rigid parabolic (TBC), Advanco rigid parabolic, General Electric rigid parabolic (PDC-1), and University of Chicago secondary concentrator. Concentrators developed by three commercial companies also were tested: Omnium-G rigid parabolic, Power Kinetics Inc. Fresnel mirror, and LaJet multiple membrane. This work, together with accompanying analysis, led to major advances in understanding the characteristics that govern the performance and cost of dish concentrators and to increased commercial interest in dish concentrator systems.

Indications are that bringing concentrator costs down to target levels will not be easy. Concentrators must be designed from the start for low-cost mass production, using good production engineering and cost-effective technology. To keep material costs down, concentrators must be lightweight and made of inexpensive materials. Nevertheless, the optical elements must withstand the weather for years (bare aluminum will not do so), and the concentrator must not be damaged by hail or blow away in gusty winds. Providing adequate strength to withstand windstorms at minimum cost is probably the most challenging problem in engineering concentrators. Single-post mounts tend to be lighter and cheaper than mounts using tracks or multiple pedestals. Field labor costs are high in the U.S.; therefore, the initial design should minimize field assembly and alignment. Inexpensive foundations are needed; in the southwestern U.S., for example, pier foundations are usually cheaper than concrete pads.

B. RECEIVERS

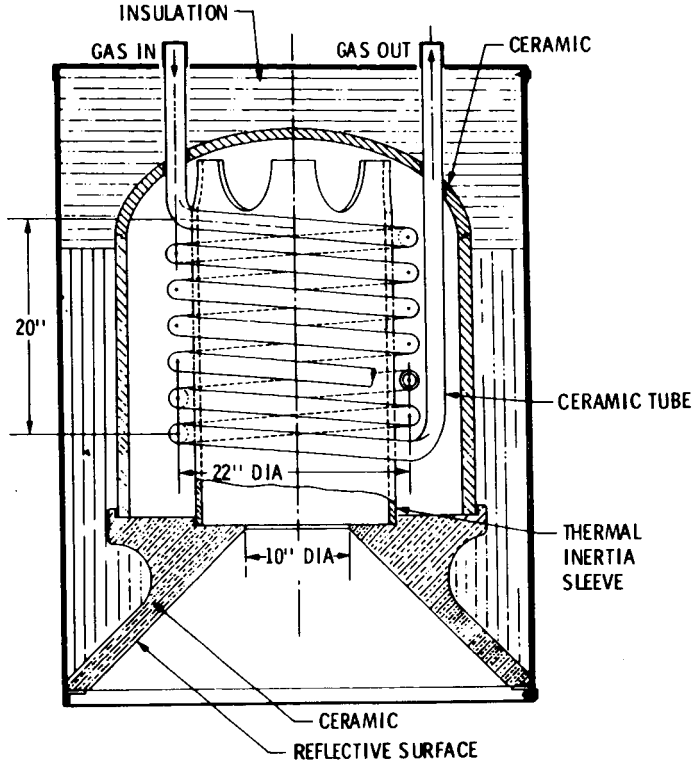
1. Receiver Characteristics

The receiver is a critical component of a parabolic dish module because it transfers the heat from the concentrated solar beam to a suitable medium (water, steam, non-condensing gas, molten salt, or metallic or organic liquid) that can produce useful energy. This medium (the working fluid or a heat transfer fluid) can supply energy directly for process heat or fuels and chemicals applications or can be used to power a heat engine for electricity production. Concentrated solar energy enters the receiver through the aperture (opening) at one end and strikes the heat-absorbing surface of the receiver's inner cavity, which is typically metal or a ceramic material. The working fluid circulates through coils (Figure 2-16a) or a matrix structure, such as a honeycomb (Figure 2-16b), near the cavity surface and is heated by the absorbed solar energy. The inner cavity is surrounded by insulation and a protective outer shell, which provides inlet and outlet passages for the working fluid and a means for mounting the receiver to a concentrator and/or for integrating it to the heat engine. Receivers also may require flow controls to prevent catastrophic heating or to smooth out transients (uneven heating) during start-up and shutdown (Reference 39).

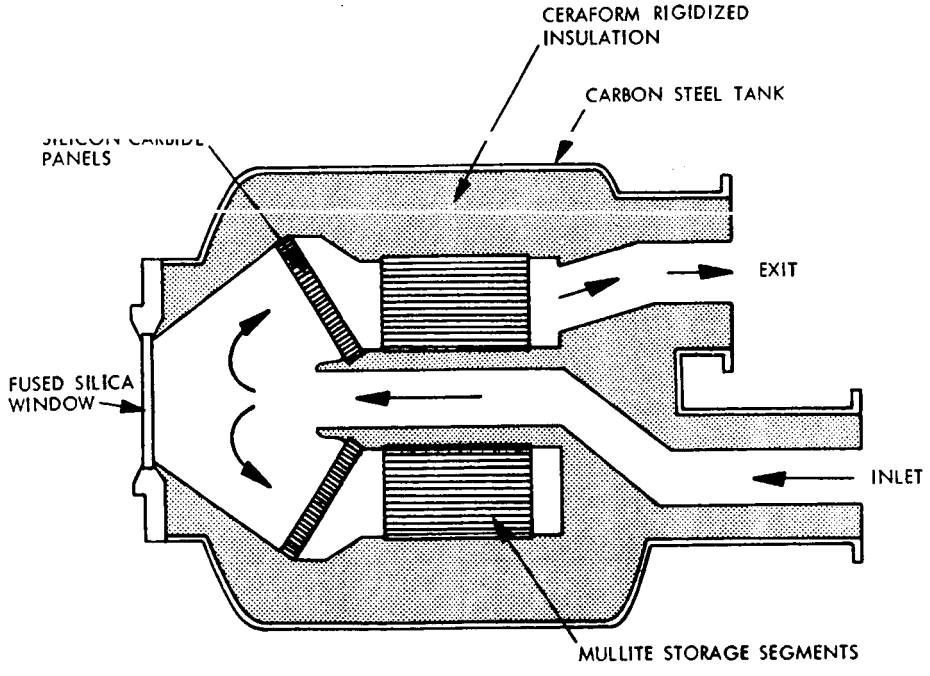
Receivers are usually classified according to the working fluid and/or the engine for which they provide thermal input. Brayton receivers are either open-cycle (using air as a working fluid at below ambient or higher than atmospheric pressures) or closed-cycle (using helium or other gases at several atmospheres pressure). These receivers require a relatively large heat exchanger area within a compact size because of the gaseous working fluid. Stirling receivers typically use helium or hydrogen as the working fluid at pressures up to 200 atmospheres and require efficient heat exchangers that provide minimal volume. Rankine receivers use water/steam or organic fluids and may also use liquid metals or molten salts in an intermediate transport loop between the receiver and working fluid.

2. Optical and Thermal Characteristics

Design of a solar receiver must consider the optical properties of the concentrator as well as the orientation of the receiver to the concentrator. To evaluate the properties of the solar flux into the receiver, models have been developed in which the sun is an extended, finite-size source and its radiation is analyzed by using cones (rather than rays) as the basic description for energy transport. Such solar simulations (Reference 40) can determine the best concentration ratio as a function of the heat flux impinging on the heat transfer surface, the concentrator reflectance, the local solar insolation, and the collector efficiency. Thermal analysis of the receiver can then be performed by entering the cavity wall incident flux information into a finite-element, thermal analyzer computer code that calculates the multiple reflections and reradiation characteristics. These calculations show that minor variations in concentrator performance (e.g., slope error of 2 mrad) will not significantly affect receiver cavity



(a)



(b)

Figure 2-16. Receiver Configurations: (a) coiled tube concept; (b) honeycomb pressurized matrix concept by Sanders Associates (see Reference 39)

efficiency for the aperture size selected. In addition, determination of cavity efficiency as a function of thermal input energy for various aperture sizes has shown that the smallest aperture consistent with concentrator optics is the most desirable (Reference 41).

3. Development Strategy

Development of solar receivers by the TPS Project proceeded along two parallel paths: one emphasizing first-generation technology and the other, advanced (second-generation) technology. Overall strategy included selection of technically attractive concepts for fabrication and performance evaluation. After determination of technical feasibility, suitable receivers were chosen for system integration tests where the performance of components would be verified while operating as part of a dish module system. Receivers developed by the TPS Project are listed and characterized in Table 2-4.

Because a receiver must meet the operating requirements of both the concentrator and engine to which it is coupled, its design requirements must consider the specific application and system configuration. These design requirements are determined by the following factors (Reference 42):

(1) Temperature and pressure needed by the power conversion or thermal process subsystem.

(2) Heat transfer characteristics defined by the working fluid.

(3) Mechanical configuration of the solar power system that includes both size and weight constraints.

(4) Optical characteristics of the concentrator.

(5) Available materials.

The goal of the Project's first-generation technology effort was to design, fabricate, and test receivers meeting the requirements listed above for various applications and configurations. Two such receivers (one air and one steam) were built in 1979-80 by Garrett AiResearch, under contract to JPL, for use with Brayton and Rankine power conversion units, respectively. These receivers are described in detail in Sections II.B.4.a and b below. Another first-generation receiver was designed and built by Ford Aerospace and Communications Corporation (FACC) for use with an organic Rankine-cycle engine as part of the Small Community Experiment (discussed in Section III). It features toluene (an organic liquid) as the working fluid and is detailed in Section II.B.4.c.

Advanced technology efforts emphasized the achievement of high-temperature (816 to 1375°C, 1500 to 2500°F) receivers required for higher-performance engines. [An advanced technology effort to build even higher-temperature receivers (required for some industrial process heat applications and fuels and chemicals processes) being carried out at JPL was transferred to the Solar Energy Research Institute in 1981 (see Reference 3).]

Table 2-4. Receivers Developed by the TPS Project (see Reference 43)

Manufacturer	Engine Cycle	Working Fluid	Cavity Material	Aperture Diameter, cm (in.)	Fluid Outlet Temperature, °C (°F)	Maximum Pressure, MPa (psi)	Efficiency, %	Other Features
Fairchild/ Stratos Division	Stirling	helium	metal (Inconel 617 tubes and sheet with copper matrix)	27.9 (11)	816 (1500)	14 (2000)	85 (est.)	Hybrid design.
Ford Aerospace & Communications Corporation	Rankine	toluene	metal (stainless steel tubes brazed to copper shell)	38 (15)	399 (750)	5.5 (790)	95 (measured)	135 kg_m (300 lb_m) of copper acts as integral buffer storage.
Garrett AiResearch	Brayton	air	metal (Inconel 625 plate fin matrix)	25.4 (10)	816 (1500)	0.34 (50)	70 to 80	
Garrett AiResearch	Rankine	steam	metal (Inconel 625 or stainless steel helical tube coils)	22.8 (9)	704 (1300)	14 (2000)	80 to 92	Reheat section and movable plate at top of cavity.
General[a] Electric	Stirling	sodium (with molten salt intermediate loop)	metal (primary and secondary heat pipes)	?	830 (1520)	?	85 to 90 (est.)	NaF-MgF_2 eutectic salt provides latent heat storage. Hybrid design.
Sanders Associates	Brayton	air	ceramic (sintered beta-silicon carbide honeycomb matrix)	19.7 (7.75)	1370 (2500)	0.7 (100)	70 (<60 at 1370°C)	Buffer storage (ceramic matrix). Fused silica aperture window.

[a]Funding reallocations precluded fabrication of a complete test unit.

Second-generation receivers also aim to maximize efficiency, provide a lifetime of 20 to 30 years with minimum maintenance, and have an acceptable mass production cost (see Reference 42).

Receiver concepts by Fairchild/Stratos Division and General Electric (GE) were evaluated for use with a Stirling engine under the TPS Project's advanced technology program. The Fairchild receiver consists of a metal tube encased in a copper slab and operates from either solar or fossil fuel at a temperature of 816°C (1500°F). The GE heat pipe receiver features thermal storage as well as hybrid operation. A Sanders Associates receiver, suited for use with a Brayton engine and based on a ceramic honeycomb matrix heated through a quartz window, was evaluated for operation between approximately 1100 and 1375°C (2000 and 2500°F) for a thermal output of 75 kW. These three advanced receivers are discussed in Sections II.B.4.d, e, and f.

In a special test program funded jointly by DOE and United Stirling, the feasibility of a commercial solar receiver was demonstrated. Five United Stirling experimental solar-only receivers were successfully operated with a Stirling-cycle engine at the focus of a test bed concentrator. These receivers and the results of the test program are described in Section II.B.4.g.

4. Development of Candidate Concepts

During 1977 and 1978, the goal of the TPS Project's receiver development task was to provide efficient, cost-effective receivers for use with compatible concentrators and power conversion units as required for the development of various types of dish modules. During this time, the Project let six contracts to industrial firms for conceptual designs of first-generation receivers: Four gas receivers suitable for use with an open-cycle Brayton engine (having a turbine inlet temperature of 816°C, or 1500°F) and two steam receivers (once-through to superheated steam at 540°C, or 1000°F, and up to 14 MPa, or 2000 psi) for use with a Rankine-cycle engine. Table 2-5 lists the contractors and corresponding receiver types and configurations selected. Cross-sectional drawings (also listing receiver characteristics) are shown for the Brayton and Rankine designs in Figures 2-17 and 2-18, respectively.

To facilitate effective management and technical support of these design contracts, a JPL design team analyzed steam Rankine and air Brayton receiver parameters, including fluid flow, heat transfer, and material stress. The geometrical distribution of solar energy on the interior surfaces of the receiver cavity is a critical variable influencing receiver design. Therefore, the JPL-developed flux mapper (see Section II.A.4.a) was used during receiver prototype testing to measure the concentrated flux in three dimensions and to determine its geometrical distribution. In addition, a computer simulation model, HEAP, was developed in order to aid in receiver characterization (Reference 44).

By December 1978, the contractors completed their preliminary designs, which incorporated ten-minute buffer storage and included complete parametric analyses, estimates of initial production costs, and proposals for final

Table 2-5. First-Generation Receiver Preliminary Designs

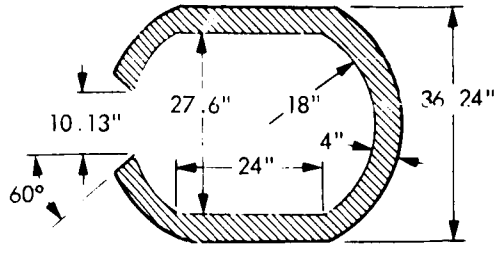
Contractor	Type	Configuration
Garrett AiResearch, Los Angeles, CA	Air Brayton Steam Rankine	Plate fin Tubular with steam drum
Boeing Engineering and Construction, Seattle, WA	Air Brayton	Tubular
Sanders Associates, Nashua, NH	Air Brayton	Ceramic core
Dynatherm Corporation, Cockeysville, MD	Air Brayton	Heat pipe
Fairchild/Stratos Division, Manhattan Beach, CA	Steam Rankine	Coil

designs and fabrication of prototypes. Of the six final design proposals that were submitted the following January, two were selected for development: one for an open-cycle air Brayton receiver and the second for a steam Rankine receiver. Contracts for both designs were awarded to Garrett AiResearch in mid-1979 (see Reference 17).

Garrett Air Brayton Receiver

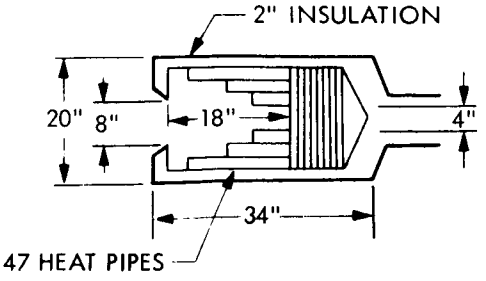
Description. The Garrett air receiver was designed to operate from an input of 85 kWt, supplied by solar flux from a dish concentrator, to heat the working gas of a highly recuperated open-cycle gas turbine Brayton engine from a temperature of 565 to 816°C (1049 to 1500°F). A metallic (Inconel 625) plate-fin heat transfer surface, shown in Figure 2-19, is used to effect this energy transfer. The inner receiver cavity is composed of the transfer surface (a single-sandwich panel) surrounded by an inner cylindrical assembly with approximately 0.11 m (4.5 in.) of insulation between the panel and the housing. The panel contains a high-density offset fin matrix having 4.72 fins per centimeter (12 fins per inch) that are brazed to the two metal sheets. Air (at 565°C) from the Brayton engine recuperator is ducted to a toroidal manifold at the bottom of the panel where it flows up the annular passage that defines the vertical walls of the inner cylindrical assembly and is heated to a temperature of 816°C. This high-temperature air is then collected in another toroidal manifold at the top of the receiver cavity and is ducted to the engine's turbine inlet at a pressure of 0.25 MPa (37 psia). The cavity assembly is enclosed in an outer cylindrical case approximately 0.76 m (30 in.) in diameter by 1.71 m (46 in.) long. The receiver aperture end is a silicon carbide cone assembly that forms a circular opening through which concentrated solar energy enters during operation. Brackets on the surface of the case are used to mount the receiver at the concentractor focal plane by attachment to a mounting ring (see Reference 41).

GARRETT PLATE FIN DESIGN



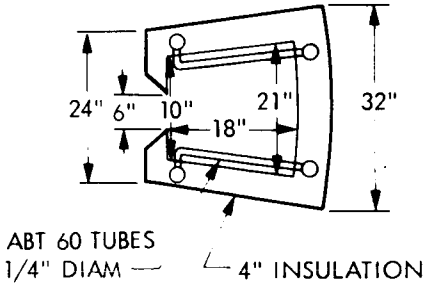
CAPACITY: 62 kWth
WEIGHT: 325 lbs WITH INSULATION
MATERIAL: HASTELLOY
INSULATION: MIN-K 2000
STORAGE TYPE: INTEGRAL OR SEPARATE MOLTEN SALT (NaCl)
WEIGHT OF STORAGE: 325 lbs
THERMAL EFFICIENCY: 84%

DYNATHERM CORP.



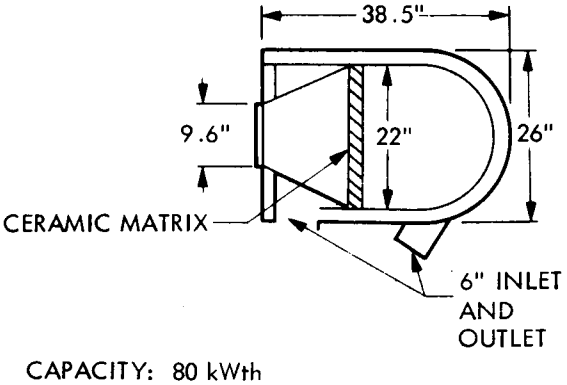
CAPACITY: 100 kWth
WEIGHT: 700 lbs INCLUDING STORAGE
MATERIAL: STAINLESS STEEL OR SUPERALLOY
INSULATION: NOT SPECIFIED
STORAGE TYPE: INTEGRAL MOLTEN SALT (LiF/NaF/MgF)
WEIGHT OF STORAGE: INCLUDED IN ABOVE
THERMAL EFFICIENCY: 95%

BOEING ENG AND CONST.



CAPACITY: 90 kWth
WEIGHT: 300 lbs
MATERIAL: INCONEL 617
INSULATION: KAOWOOL BLANKET AND BLOCK
STORAGE TYPE: ① SENSIBLE HEAT IN REFRACTORY SPHERES OR ② BATTERY
WEIGHT OF STORAGE: ① 1000 lbs ② 50 lbs
THERMAL EFFICIENCY: 87.4% (NOT COUNTING SPILLAGE) 77 8% WITH 11% SPILLAGE

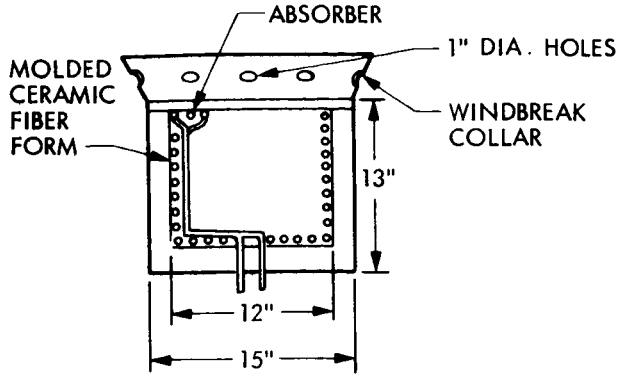
SANDERS ASSOCIATES



CAPACITY: 80 kWth
WEIGHT: 150 lbs
MATERIAL: STAINLESS STEEL
INSULATION: THERMO 12
STORAGE TYPE: SEPARATE SENSIBLE HEAT IN REFRACTORY BLOCKS
WEIGHT OF STORAGE: 300 lbs
THERMAL EFFICIENCY: 86%

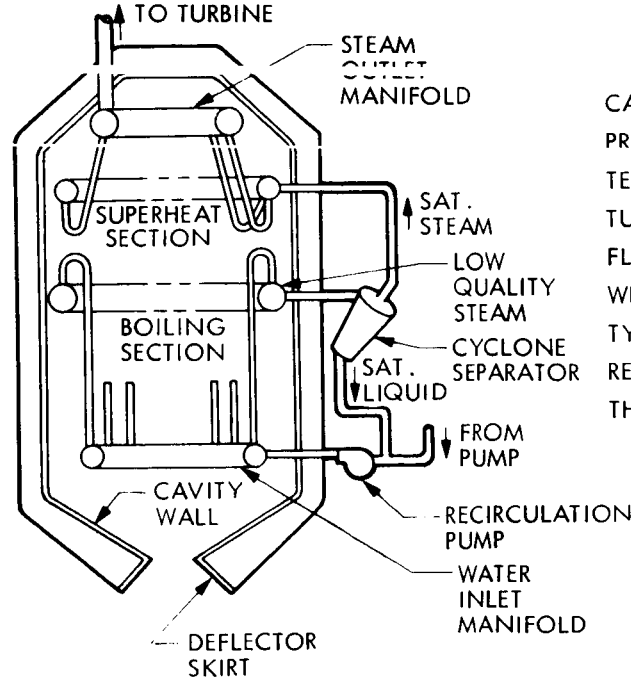
Figure 2-17. Proposed Air Brayton Receiver Designs (see Reference 14)

FAIRCHILD STRATOS



CAPACITY: 90 kWth
PRESSURE: 1500 psi
TEMPERATURE: 1200°F
TUBE MATERIAL: STAINLESS STEEL
FLOW RATE: 2.5 lbs/hr kWth
WEIGHT: 75 lbs
TYPE: ONCE THROUGH TO SUPERHEAT
REHEAT CAPABILITY: WITH MINOR MODS
THERMAL EFFICIENCY: 80-90%

GARRETT AIRESEARCH



CAPACITY: 50-90 kWth
PRESSURE: 1500 psi
TEMPERATURE: 1200°F
TUBE MATERIAL: STAINLESS STEEL
FLOW RATE: 2.5 lbs/hr kWth
WEIGHT: 200 lbs
TYPE: SEPARATE BOILER/SUPERHEATER
REHEAT CAPABILITY: WITH MINOR MODS
THERMAL EFFICIENCY: 80-90%

Figure 2-18. Proposed Steam Rankine Receiver Designs (see Reference 14)

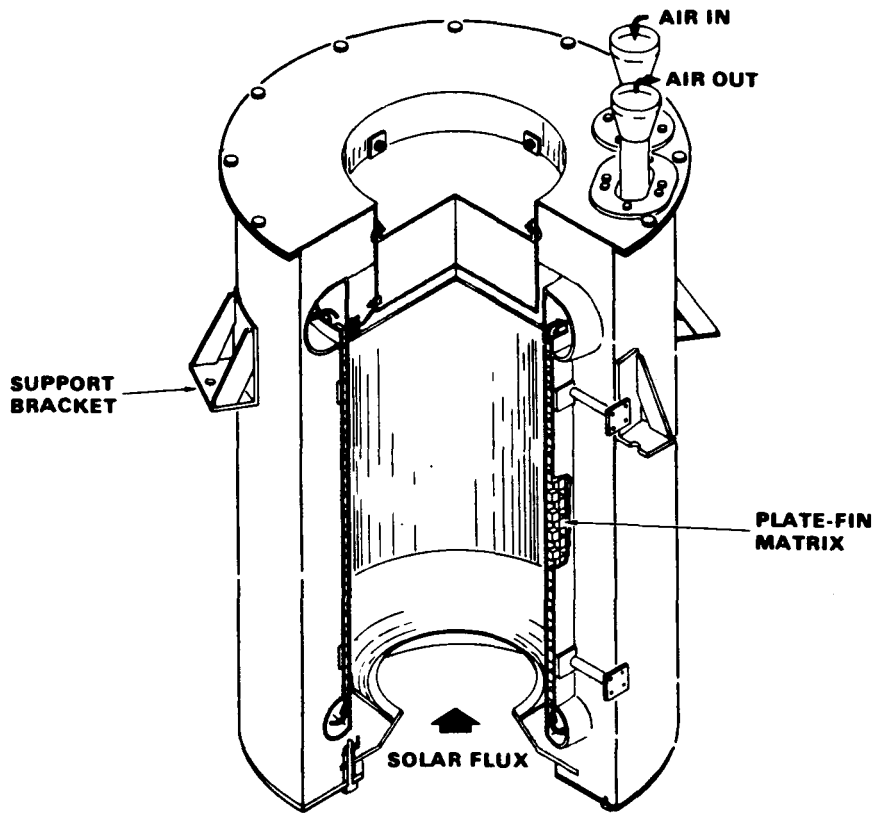


Figure 2-19. Cross-Sectional Diagram of the Garrett Air Brayton Receiver

Test and Evaluation. After delivery to the Parabolic Dish Test Site in December 1980, the completed air receiver (shown in Figure 2-20) was instrumented and installed at the focal plane of a test bed concentrator. During testing, which was completed in May 1981, the receiver's operating range (including temperature, pressure, and flow rate) was established. Even though performance goals were met, it was determined that high thermal gradients in the Inconel heat exchanger produced stresses that would decrease its lifetime significantly. Solutions to this problem were formulated that could be applied in the fabrication of future units (see Reference 42).

b. Garrett Steam Rankine Receiver

Description. The steam receiver by Garrett AiResearch is designed to supply process heat as well as energy for powering a steam Rankine power conversion unit. The latter application can utilize the reheat option. In each case, the receiver operates from a peak solar input of 85 kWt at a maximum pressure of 14 MPa (2000 psi) and a temperature of 704°C (1300°F). Two helical tube coils form the interior cavity walls. The pre-heat boiling coil is located adjacent to the aperture and is an 1.11-cm (0.44-in.) tube with a coil diameter of 0.43 m (17 in.) and a length of 0.371 m (14.6 in.). The reheat coil is a 1.8-cm (0.75-in.) tube with a coil diameter of 0.43 m (17 in.) and a length of 0.175 m (6.9 in.). Both coils are Inconel 625 or type 347 stainless steel that are brazed separately and then mechanically joined

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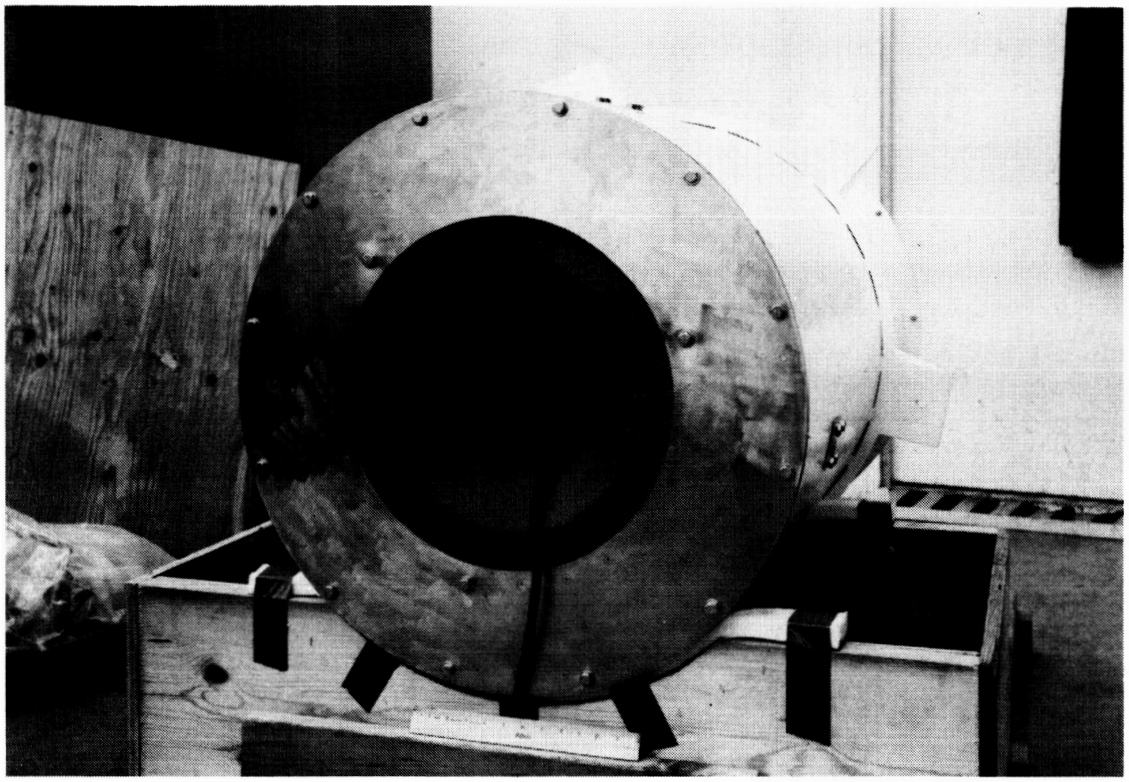

Figure 2-20. Garrett Prototype Air Brayton Receiver

together. The cavity heat transfer surfaces are separated from the 0.76-m (30-in.)-diameter outer case by approximately 10.1 cm (4 in.) of insulation. The top of the receiver cavity is an uncooled metal plate of RA 330 steel that can be adjusted in the axial direction by a screw on the exterior case (see paragraph below). The aperture assembly and mounting provisions are the same as the Garrett air Brayton receiver described immediately above. A drawing showing the steam receiver's principal components is shown in Figure 2-21 (see Reference 41).

The Garrett steam receiver's movable top end plate makes it possible to rebalance the fluid temperature to 704°C when significant variations in the flux distribution occur within the receiver cavity. Repositioning the plate toward the aperture 4 cm (1.6 in.) shields the reheat section and provides reradiation from the top plate to the rest of the cavity, thus creating the rebalancing effect.

Test and Evaluation. A prototype steam receiver (shown in Figure 2-22) was tested at the PDTS in early 1981. The receiver demonstrated stable, uniform operation over the full performance range with no evident flow instabilities, even at very low mass flow rates. Figure 2-23 shows the receiver generating steam on solar flux from a test bed concentrator. Steam from the receiver frequently was used to produce fuels and chemicals (e.g., furfural) in an experimental test setup at the PDTS. The receiver also was

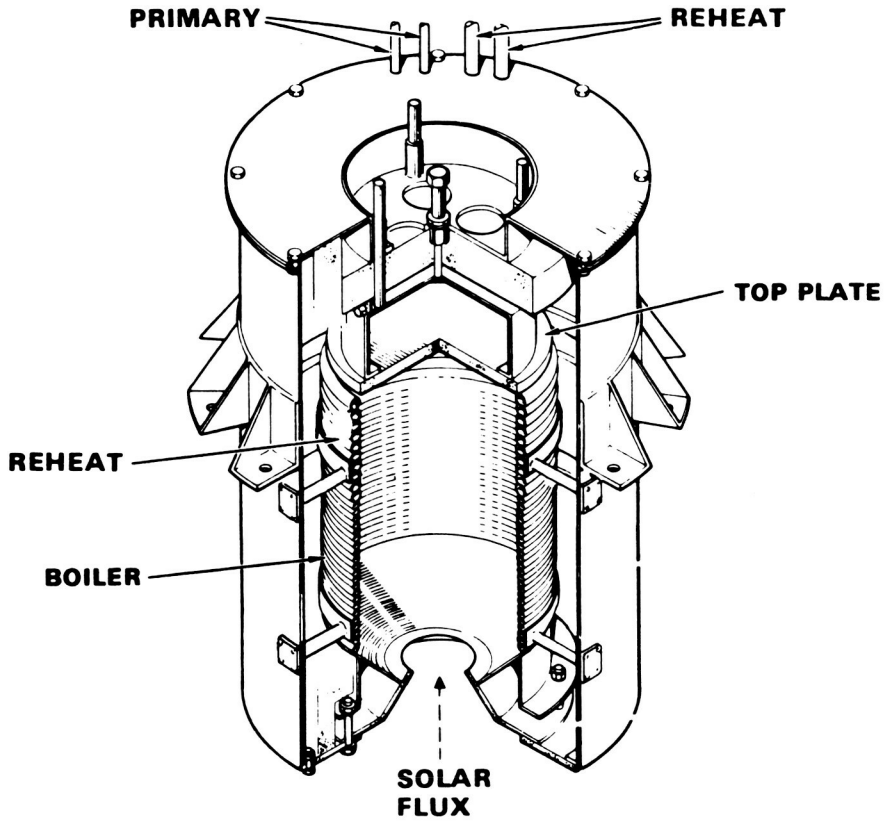

Figure 2-21. Cross-Sectional Diagram of the Garrett Steam Rankine Receiver

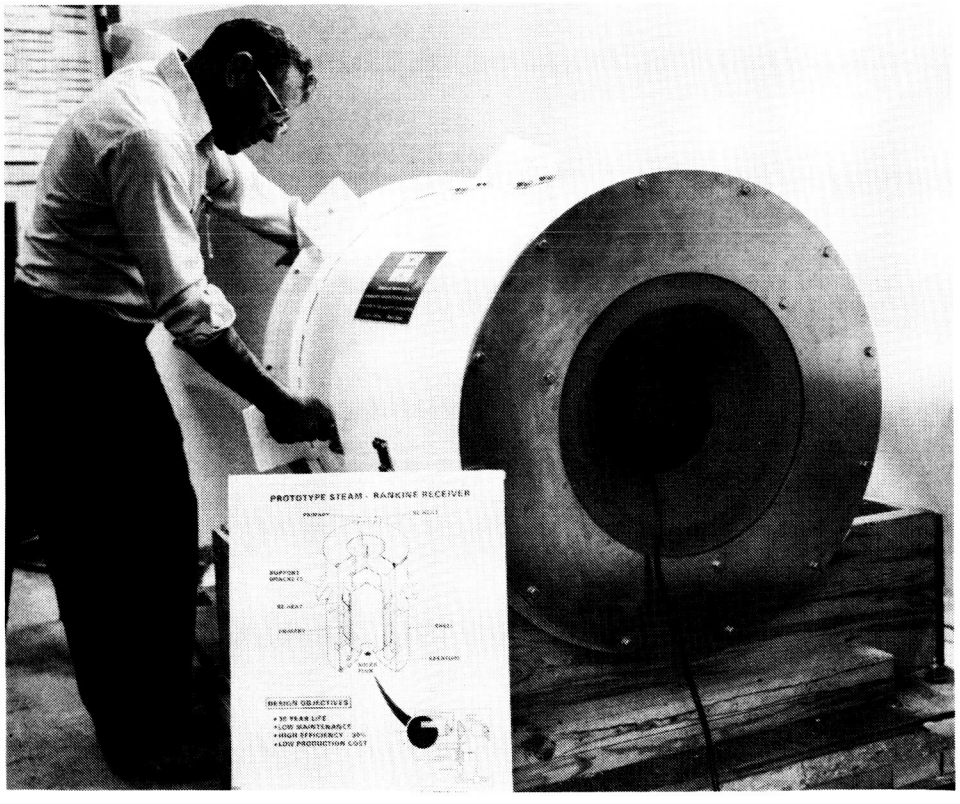

Figure 2-22. Garrett Prototype Steam Rankine Receiver

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Figure 2-23. Garrett Receiver Producing Steam During Testing at the Focal Plane of a TBC

used to test heat engines and could be used for developing aperture and cavity designs that are especially resistant to thermal shock (see Reference 42).

c. FACC Organic Rankine Receiver. Design of a first-generation receiver using toluene (an organic liquid) as the primary working fluid was approved by the TPS Project in June 1980. Ford Aerospace and Communications Corporation (FACC), the designer, proceeded to fabricate the receiver as part of their organic Rankine-cycle (ORC) module planned for use in the Small Community Experiment (discussed in Section III.A).

Description. The organic receiver, designed for a 30-year lifetime, is a direct-heated, once-through, single-tube toluene boiler capable of operating at sub- or super-critical pressures (Figure 2-24). Its cylindrical copper shell cavity is heated by a thermal input of up to 95 kW, vaporizing and raising the temperature of the toluene to 399°C (750°F) at 5.5 MPa (790 psia) as it flows through the stainless steel tubing brazed to the outer surfaces of the cavity. The thick copper-plate shell acts as "buffer" storage that inhibits flow and boiling instabilities by evenly distributing heat entering the receiver. The cavity assembly (core) is supported by eight struts, insulated with high-temperature refractory ceramic wool, and enclosed by a weather-proofed aluminum casing. The receiver aperture, 38 cm (15 in.) in diameter, is formed by a plate and lip ring made of copper (Reference 45). The qualification test receiver is shown in Figure 2-25.

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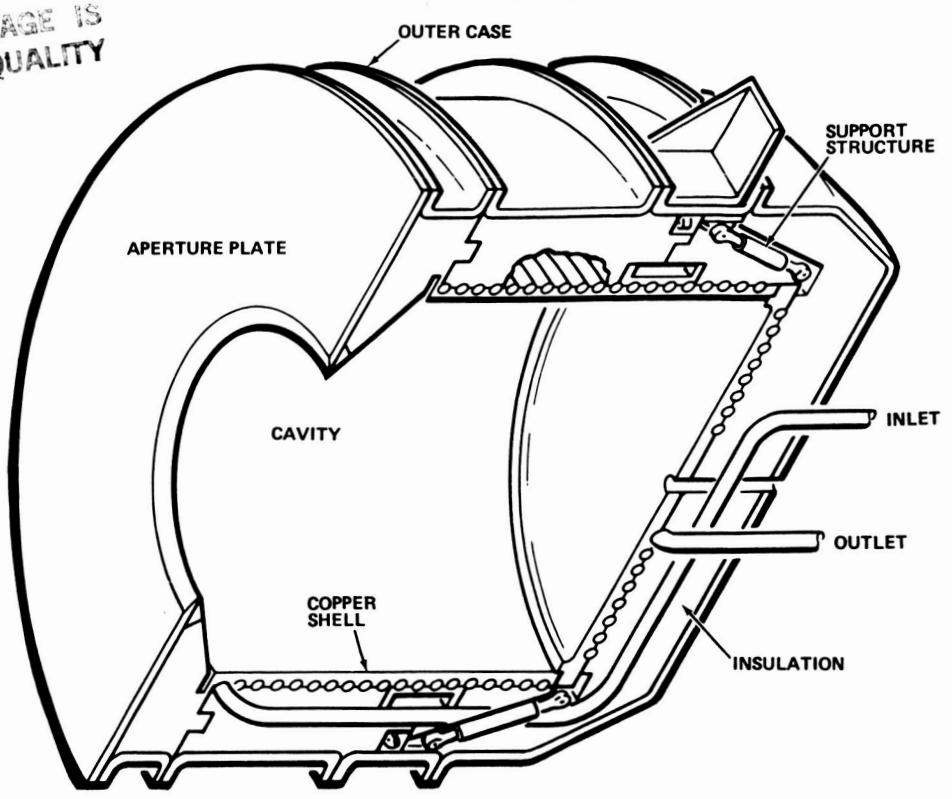

Figure 2-24. Cross-Sectional Diagram of the FACC Organic Receiver

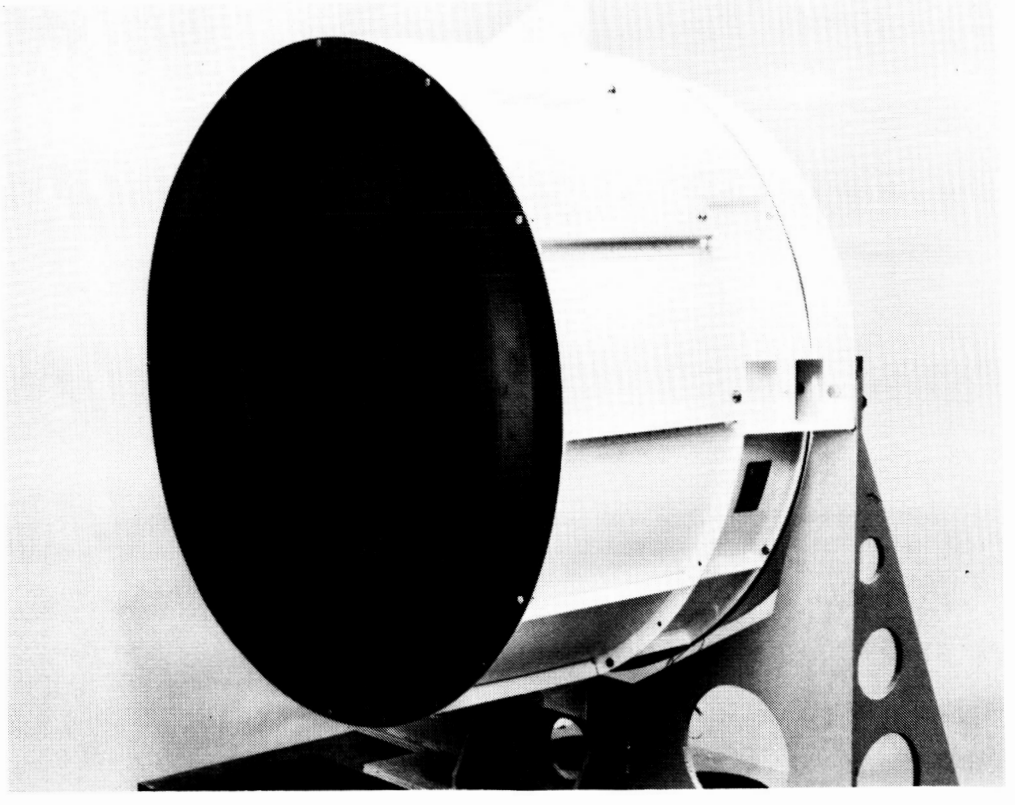

Figure 2-25. FACC Organic Receiver Prior to Engine Integration

Test and Evaluation. In early 1981, FACC began testing the ORC receiver under steady-state conditions, using a test loop to simulate the Rankine heat engine. The receiver was subjected to sub- and super-critical toluene pressures and thermal outputs between 25 and 100 kWt. Subsequent to these successful qualification tests, the receiver was integrally attached to the ORC engine, then shipped to the PDTS for solar testing that took place from November 1981 to March 1982 (see Reference 42). The complete ORC power conversion assembly operated successfully over a complete range of operating conditions, and a receiver efficiency of 95% was measured. These tests verified the compatibility of the receiver with other ORC module components.

d. Fairchild Stirling Receiver. The Stirling receiver designed and fabricated by Fairchild/Stratos Division resulted from an effort by the Project in 1979 to develop an advanced receiver suitable for use with a USAB (United Stirling AB) engine. This effort also included the design of a receiver by General Electric (discussed below). Both the Fairchild and GE designs feature a hybrid capability that allows thermal augmentation by a gaseous fossil fuel to provide continuous power and eliminate the need for storage. Stirling receivers also should be designed so that the engine-cycle dead space is minimal.

Description. The Fairchild Stirling receiver uses helium as the working fluid and operates on 76.5 kWt from a dish concentrator or on 70.0 kWt from fossil fuel combustion. The surface of the receiver's cavity is a copper conical plate with integral spaces through which the helium passes. The passages are formed by tubes made of Inconel 617 embedded in a copper matrix that is, in turn, encapsulated by an Inconel 617 sheet. The conical plate is heated by solar radiation and also by combustion gas on the back surface and the regenerator tubes. The receiver's design operating ranges are 650 to 816°C (1200 to 1500°F) and 10.5 to 14 MPa (1500 to 2000 psi) when directly coupled to the cylinders and regenerator housings of a Stirling engine (Figure 2-26).

Test and Evaluation. Combustion and heat transfer tests were conducted at Fairchild by JPL, Fairchild, and the Institute of Gas Technology. After reliable cold-start performance, full design output power, and turndown capability were demonstrated (Reference 46), the receiver was shipped to JPL in December 1980 for combustor and preheater tests. Fully integrated testing of the receiver and the power conversion unit at United Stirling in Sweden resulted in leaks in the heater heads. The heads were subsequently repaired by the manufacturing subcontractor, Solar Turbines International.

In September 1981, the complete Stirling engine/receiver power conversion assembly (PCA) was installed on a test bed concentrator by personnel from JPL, United Stirling AB of Sweden, and Advanco Corporation, which was responsible for PCA integration and functional testing. The PCA operated in a hybrid mode at heater head temperatures of up to 770°C (1420°F), mean engine pressures of 11 MPa (1625 psia), and solar thermal inputs up to 20 kW with 25% of the TBC facets uncovered. Testing was terminated after the PCA generated 15 kWe (which were fed into the Southern California Edison

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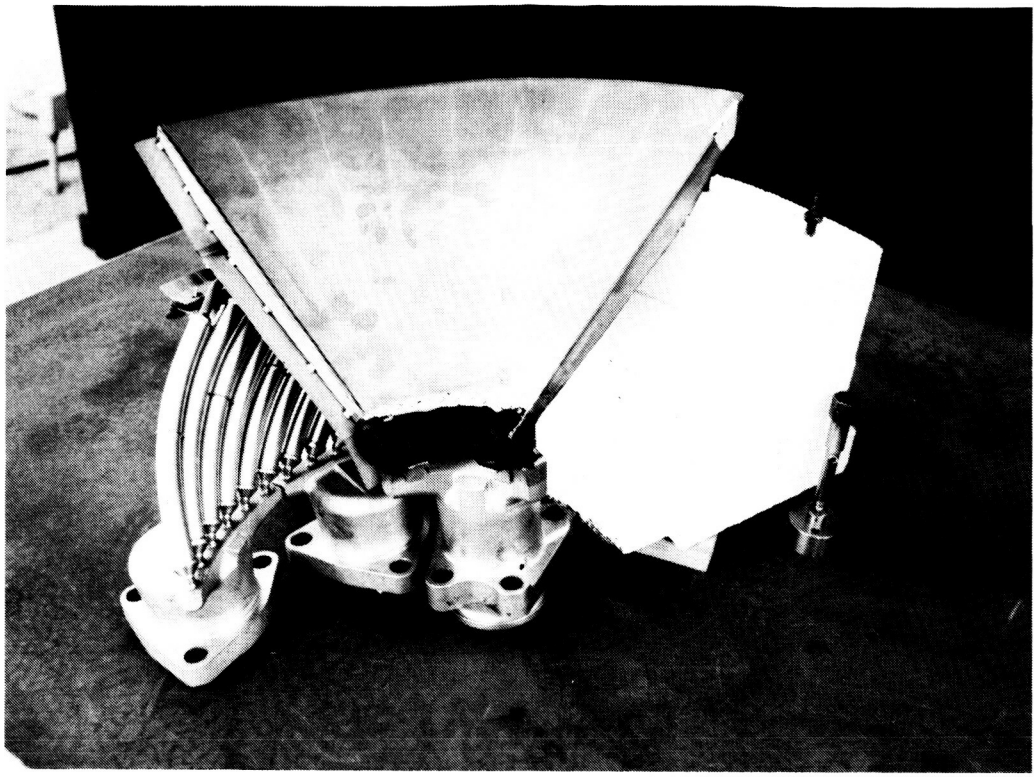

Figure 2-26. Fairchild Receiver/Stirling Engine Quadrant and Burner

distribution grid) from 50% of the TBC mirror facets. This thermal input caused failures in the receiver heater head when hot combustor gas impingement caused the braze joint on the outermost heater head tube to open. Funds have not been available for the redesign and repair required to enable further performance testing of the hybrid system (see Reference 36).

e. General Electric Stirling Receiver

Description. The General Electric preliminary design of a heat pipe Stirling receiver featuring energy storage is shown in Figure 2-27. It consists of fourteen primary heat pipes and one secondary heat pipe, all containing sodium for high-temperature operation. The secondary heat pipe is embedded in sodium-fluoride/magnesium-fluoride ($NaF-MgF_2$) eutectic salt that provides latent heat storage. A natural gas combustor with a set of tertiary heat pipes for transporting heat to the large secondary heat pipe allows hybrid (fossil-fuel/solar) operation. The receiver is designed to operate with a 24-kWe Stirling engine at a temperature of approximately 830°C (1520°F) and to provide 48 minutes of thermal storage.

Preliminary Testing. A modular experiment was conducted at General Electric on a single primary heat pipe and a secondary heat pipe containing three standard design salt containers and a heat extraction coil to simulate a Stirling engine. The test apparatus performed successfully at all

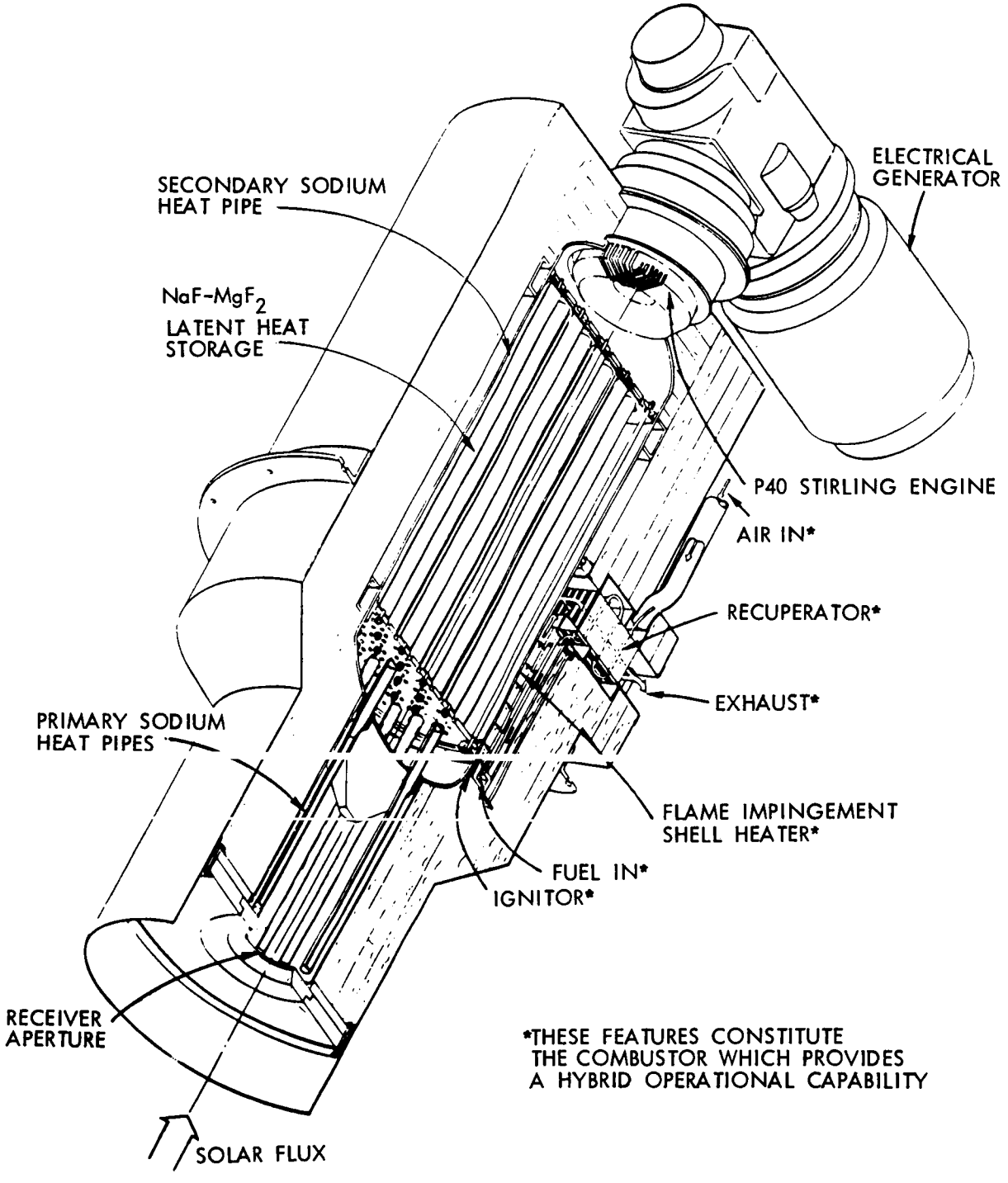

Figure 2-27. GE Heat Pipe Stirling Receiver Concept

operating angles and modes (Reference 47). These tests also provided data for defining the operating characteristics of the thermal transport and storage systems (see Reference 27). Funding reallocations by the Department of Energy precluded fabrication of a complete test unit.

f. Sanders Air Brayton Receiver

Description. Early in 1980, Sanders Associates was contracted to design and build a high-temperature (1370°C, 2500°F) air receiver using a ceramic honeycomb and operating at 2 atmospheres. (Refer to Figure 2-16b.) Solar energy passes through a fused silica window and directly heats the honeycomb matrix (shown in Figure 2-28). Air (or another suitable gas) flows through the honeycomb, extracts the energy, then passes through a short-term (buffer) ceramic storage matrix before exiting the receiver. The directly heated matrix is made from sintered beta-silicon carbide; the storage matrix is made from mullite. The cavity assembly is encased in a carbon steel housing that is 1.2 m (47.2 in.) long and 0.75 m (30 in.) in diameter. The first test unit of this type of receiver is shown in Figure 2-29.

Test and Evaluation. Upon completion of fabrication in September 1980, Sanders conducted in-house testing before delivery to the PDTS for solar performance and interface compatibility tests. The latter included testing at different power levels from one quarter (25% of TBC mirror facets uncovered) to full power, or about 20 to 80 kWt input, and at various inlet and outlet temperatures. At full power, receiver outlet temperatures of from

Figure 2-28. A 30-deg Sector of Ceramic Honeycomb Matrix

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870 to 1425°C (1600 to 2600°F) were achieved (see Reference 34). Estimates of efficiency are 60% at 1200°C (2200°F) and 70% at 870°F (1600°F), accounting for aperture losses (see Reference 29).

Results of the Sanders receiver test program demonstrated the feasibility of this concept for system configurations requiring exit air temperatures above those attainable with state-of-the-art metal designs. A modified version of this ceramic receiver is used in a parabolic dish module employing a recuperated subatmospheric Brayton-cycle engine (Reference 48) (see Section III).

g. Experimental Solar-Only Receivers. Five United Stirling experimental solar-only receivers (ESORs) were successfully operated with a Stirling-cycle engine at the JPL Parabolic Dish Test Site from 1982 to 1984 under a test program funded jointly by DOE and the receiver manufacturer. Objectives of the test program were to gain practical operating experience, to improve the performance of the Stirling power conversion unit (PCU), and to establish the feasibility of fabricating commercial solar receivers.

The experimental solar-only receivers, which differ primarily in construction of the tube-manifold of the heater, are described in Table 2-6. All were operated for many hours with no failures although burnout of three receivers occurred because of operator error. The damaged receivers were repaired by brazing in replacement tubes (Reference 49).

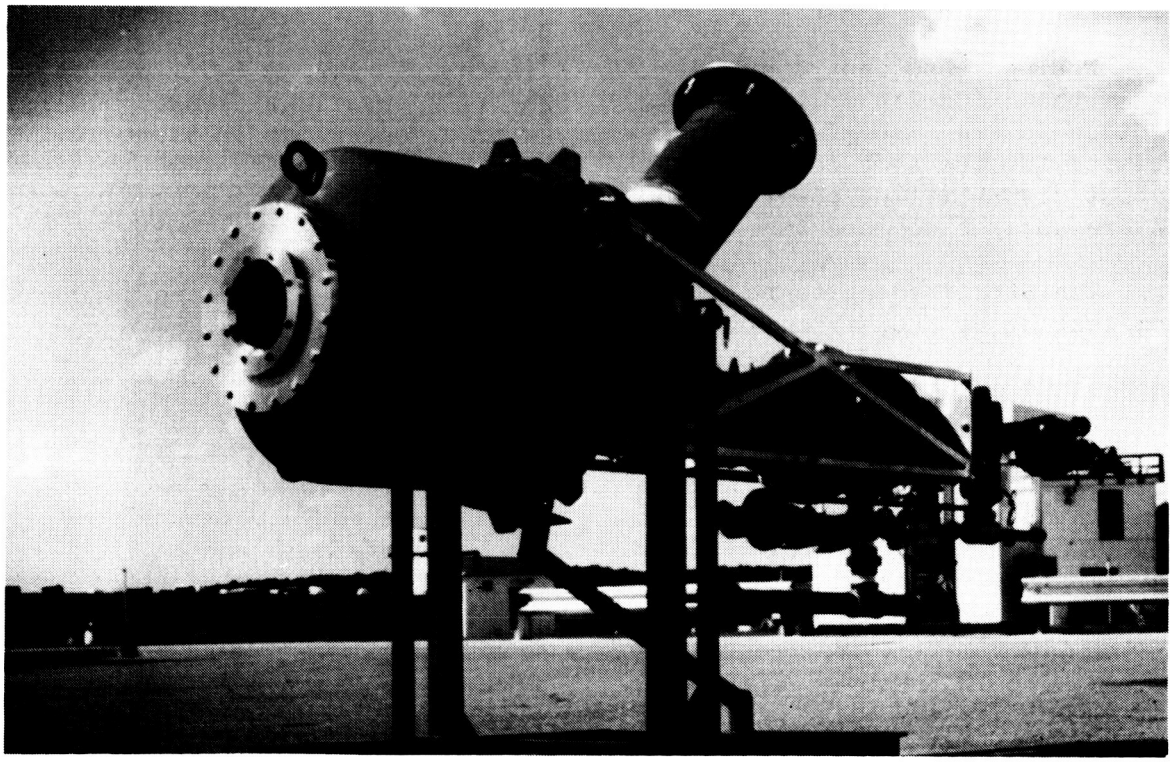

Figure 2-29. Sanders Ceramic Receiver Test Unit

Table 2-6. United Stirling Experimental Solar-Only Receivers Tested at the PDTS (see Reference 49)

Receiver Designation	Description
ESOR-I	Standard combustion system heater
ESOR-IIA	Solar-only receiver with manifold
ESOR-IIB	Solar-only receiver with only single tubes
ESOR-III	Solar-only receiver with only single tubes but with increased diameter and tubes of the "hair pin" type
ESOR-IV	Optimized receiver for solar application with consideration of production cost

A comparison of data collected during testing of ESOR-IIA and IIB, operating with helium (He) and hydrogen (H_2) and with different concentrator alignments, is presented in Table 2-7. Results of this comparison show that concentrator alignment produces a first-order effect on Stirling PCU performance, i.e., efficiency of the PCU improves with increasing thermal input from the concentrator (Reference 50).

During subsequent testing, ESOR-III (shown in Figure 2-30) performed better than ESOR-IIA or IIB. Because ESOR-III's tube length was optimized in relation to the outer receiver diameter, a lower operating pressure was achieved for the same output power. It was shown that, with ESOR-III, the highest dish/Stirling power subsystem output can be attained with a working gas pressure of no more than 20 MPa (see Reference 50).

The Stirling engine test program at the PDTS was terminated before data from testing of ESOR-IV could be evaluated.

5. Receiver Technology Assessment Summary

The TPS project paid particular attention to solar receivers. Even though receivers are much less costly than concentrators or engines, they are the essential link in the power cycle between the dish and engine, providing the variability in the power chain that allows optimization of the more costly components. A number of receiver concepts were developed and several prototypes built and tested to provide empirical proof of the design methods. These included water/steam boilers, both single-phase and boiling liquid heaters, and metal and ceramic gas heaters. Temperatures ranged from around 150°C (300°F) to the 1425°C (2600°F) outlet temperature of the Sanders high-temperature solar receiver. Pressures ranged from below atmospheric pressure air up to the over 14-MPa (2000-psia) steam outlet of the Garrett

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Table 2-7. Results of ESOR-IIA and IIB Testing with Different Concentrator Alignments (see Reference 50)

Receiver Type	Date (1982)	Working Gas	Engine Output, kWe	Max. Pressure, MPa	Gas Temp., °C	Insolation, W/m^2	Input, kWt	Efficiency, %
ESOR-IIA	March	He	19.5	17.3	700	915	68.6	28.4
ESOR-IIB	March	H_2	20.7	15.3	680	980	73.5	28.2
	March	He	19.5	17.0	690	973	73.0	26.7
ESOR-IIA	July	H_2	24.2	19.7	704	960	72.0	33.6
	July	He	20.7	19.4	700	906	67.9	30.5
ESOR-IIB	June	H_2	22.4	17.6	699	898	67.3	33.2
	June	He	20.6	18.6	691	922	69.2	30.0

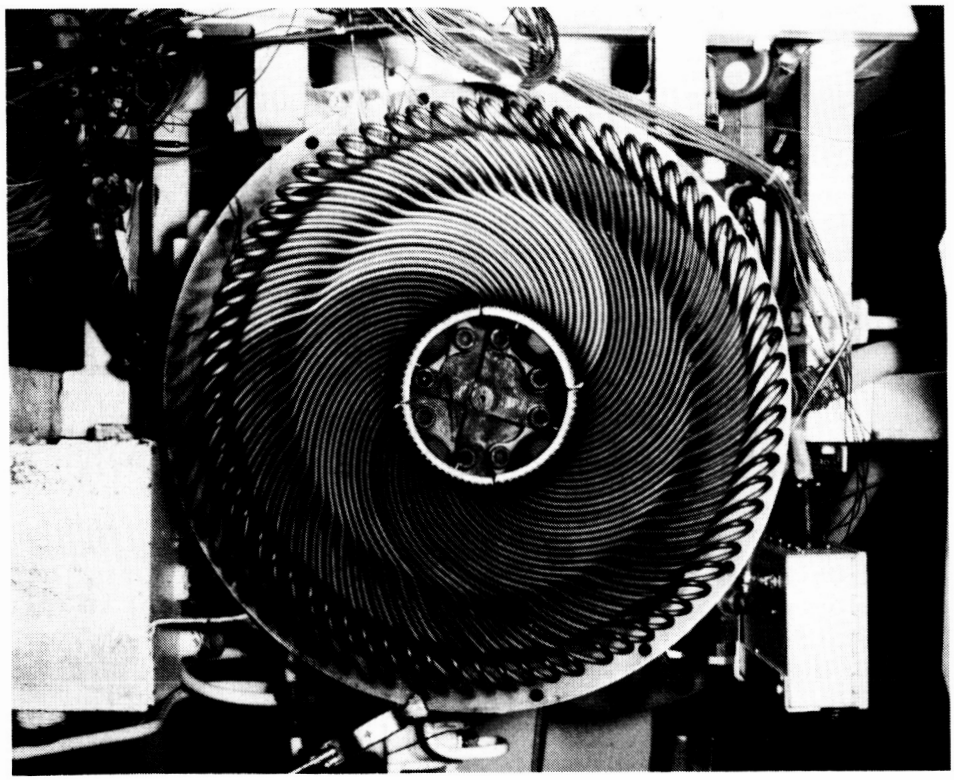


Figure 2-30. ESOR-III

steam receiver. Heat transfer fluids included water, organic liquids, and a variety of gases. Special heat exchangers were developed to accommodate system requirements such as (1) the need for symmetry and low volume for the Stirling cycle, (2) low pressure drop at high temperatures for the Brayton, and (3) two-phase flow in boiling Rankine systems. This wide variety of operating needs proved that highly efficient solar receivers were practical and attainable with careful design methods. Experimental work centered mainly on thermal engineering problems unique to solar receivers. This included the need to emphasize cavity dynamics for balancing convective and radiative losses from the cavity aperture. Another element receiving concentrated effort was the development of passive aperture plate materials of reasonable cost that could withstand the intense heat of solar "walk-off" (Reference 51). Also included was work on methods to accommodate the non-uniform heat distribution on the cavity walls by enhancing axial conduction and providing superior forced cooling in regions of high flux. Thus, by combining a variety of advanced heat transfer techniques into the cavity receiver, long-lived, highly efficient solar receivers were proven practical and cost-effective.

C. POWER CONVERSION UNITS

1. Engine Characteristics

Engines for parabolic dish-electric modules have characteristics that distinguish them from automotive or any other off-the-shelf engine. A parabolic dish engine must be relatively small: As engine size and power increase, so does the dish area required to provide the optimal solar flux for engine operation. It has been determined that power converters in the range of 15 to 25 kWe are suitable for use with dish concentrators of about 11 m in diameter. Engines larger than automotive-size require such large dishes that the resultant manufacturing, transportaton, and maintenance costs for the concentrator would offset the gain in engine efficiency. Engine weight is also an important consideration because it affects overall system weight and the dynamics of tracking control. All engines are inherently subjected to temperature variations and mechanical stress. In dish modules, engine stress is increased because of uneven thermal input, non-horizontal operation, and start-up and shutdown. Adequate engine lubrication and cooling are problems aggravated by the variable attitudes imposed on the engine by dish mounting.

Brayton-, Rankine-, and Stirling-cycle engines -- some available and others undergoing development -- offer the most promise for dish systems. Available small reciprocating Rankine engines operate on a simple steam cycle without reheat and have relatively low efficiency. Compound steam cycles or the use of an organic working fluid are attractive Rankine-cycle alternatives for dish power converters. Small Brayton engines considered adaptable include unregenerated Brayton units (that drive a generator and require the addition of a recuperator for acceptable efficiency), the automotive advanced gas turbine, and the subatmospheric Brayton cycle (SABC). Future Brayton engines employing ceramic parts could operate at higher temperatures (above 870°C, or 1600°F) and corresponding higher efficiencies. Stirling-cycle engines require some modification for solar use, e.g., changes to the lubrication system to allow inverted engine operation. The use of an external heat supply concept and its high thermal efficiency make the Stirling-cycle engine an attractive candidate.

2. Strategy for "Solarization"

Efficiency, reliability, and cost are the critical issues in modifying heat engines for parabolic dish-electric modules. A highly efficient power conversion unit (heat engine plus alternator and associated controls) can reduce the size of the concentrator required, but also must operate at high temperatures. Therefore, the reliability of the engine's many moving parts must be assured as they operate in this extreme environment. The engine also represents a significant part of the total module cost; hence, a trade-off exists between cost (including operation and maintenance) and efficiency (see Section IV, "System Performance and Economic Projections").

The JPL program to adapt suitable engines for dish-electric modules began in 1978 with consideration of small (15-kWe) engines designed for this purpose in conjunction with the NASA Lewis Research Center (LeRC) heat engine evaluation program. The engines that were subsequently modified for use in dish-electric solar power modules are listed in Table 2-8.

Engines considered by the JPL TPS Project as first-generation were the Rankine and air Brayton cycles, which were expected to operate at efficiencies of 25 to 35% for applications in the early 1980s and for which considerable technology was available (see Reference 14). Design studies of turbine and reciprocating Rankine engines in addition to open- and closed- cycle Brayton engines are discussed in Section II.C.3.a below. Two Rankine cycles were subsequently tested by the Project for use in dish modules aimed at the near-term small community market: (1) two simple-cycle steam engines by Jay Carter Enterprises: a 5-kWe single-cylinder steam engine, which was believed to be the only available small steam engine suitable for use with a 25-to-50 m^2 dish concentrator, and a 15-kWe two-cylinder steam engine suitable for larger concentrators; (2) an organic Rankine-cycle engine/ alternator capable of operating at higher efficiencies than steam Rankines, yet at moderate temperatures (400°C, 750°F). These two engines are described in Sections II.C.3.b and c, respectively. An open-cycle Brayton engine by Garrett AiResearch was selected for detailed design and fabrication out of the six initial design studies completed for the TPS Project. The Garrett design is to include a hybrid capability (i.e., can operate on both solar and fossil-fuel input) and is based on the automotive advanced gas turbine (AGT) being developed under the LeRC program. The "solarization" of the AGT and also of the recuperated subatmospheric engine (another promising Brayton concept) are described in Sections II.C.3.d and e.

Engines considered as second-generation (advanced) were Stirling engines and higher-temperature (above 870°C, 1600°F) Brayton engines that could achieve efficiencies of 35 to 45% and be used in dish-electric applications by 1985. An automotive Stirling engine was modified and tested in a solar mode at an efficiency of 40% (engine only, not accounting for parasitics). This JPL program to adapt a United Stirling of Sweden engine and the following extensive test series are covered in Section II.C.3.f. Ceramic Brayton engines, being pursued under the automotive advanced gas turbine engine program, could result in high-efficiency Brayton-dish modules.

Table 2-8. Engines Modified and/or Tested for Dish-Electric Modules (see Reference 29)

Manufacturer	Engine Type	Working Fluid	Input Temperature, °C (°F)	Mean Pressure, MPa (psi)	Mass Flow Rate, kg/h (lb/h)	Sink Temperature, °C (°F)	Engine Speed, rev/min	PCU[a] Output, kWe	PCU Weight, kg (lb)	PCU Efficiency, %
Barber-Nichols	Organic Rankine	Toluene	399 (750)	4.8 (700)	430 (945)	45[b] (115)	50,000	16[c]	365 (800)	23
Carter	Steam Rankine	Steam	566 (1050)	14 (2000)	27[d] (60)	?	1,800	5	?	12-15[e]
Carter	Steam Rankine	Steam	538 (1000)	7 (1000)	93 (204)	101 (215)	3,600	15.4	?	19.6
Garrett	Air Brayton (based on automotive gas turbine)	Air	870 (1600)	0.2 (30)	930 (2050)	25 (80)	80,000 to 86,000	24[f]	210 (460)	32
Garrett	Subatmospheric Brayton	Air	777 (1430)	0.1 (14.7)	?	35 (95)	60,000	?	?	?
United Stirling	Stirling	Helium or hydrogen	700 (1292)	15 (2200)	1000[g] (2200)	50 (125)	1,800	25[f]	205 (450)	34

[a]PCU (power conversion unit) or PCS (power conversion subsystem) is the engine plus alternator plus, in the case of the organic Rankine, rectifier.

[b]Condenser unit.

[c]With 86% efficient alternator.

[d]At test steam conditions of 399°C and 7.7 MPa.

[e]Expected at maximum temperature and pressure.

[f]With 94% efficient alternator.

[g]The USAB 4-95 engine system contains ~2 liters of hydrogen (STP), perhaps half of it in the engine itself. An additional 5 to 7 liters may be stored in a gas bottle reservoir. There is ~5 gm of working gas oscillating at 30 Hz between the hot and cold working volumes of the Stirling cycle. The average velocity of the g-s is roughly 40 m/s. For comparison purposes, although net flow is zero, bidirectional gas flow past a fixed point amounts to perhaps 1000 kg/h at maximum engine power.

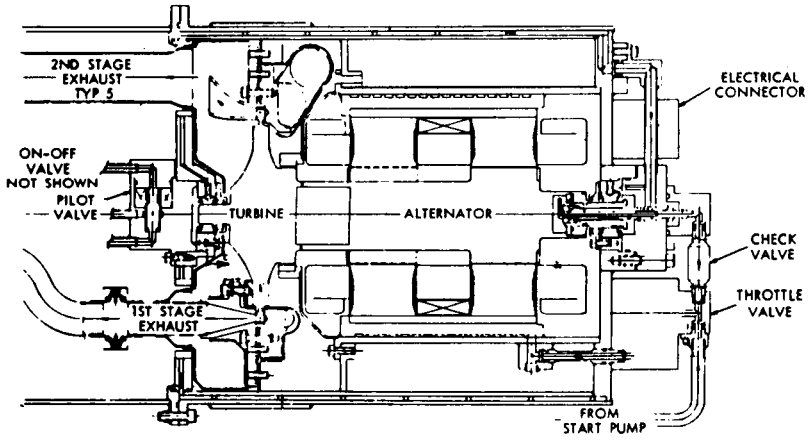
3. Adaptation and Testing of Principal Engine Cycles

a. Conceptual Design Studies (Rankine and Brayton Cycles). During 1979, conceptual design study contracts were completed for the purpose of identifying small engines (Rankine and Brayton cycles) in the 10- to 20-kWe range that could be modified for first-generation dish-electric applications by 1982 (see Reference 17). The engines studied are depicted in Figures 2-31 and 2-32 and described in Table 2-9. The studies were limited to available engines or those that could be modified using available technology. Following parametric studies, design points were selected for each engine configuration, and conceptual designs were evolved.

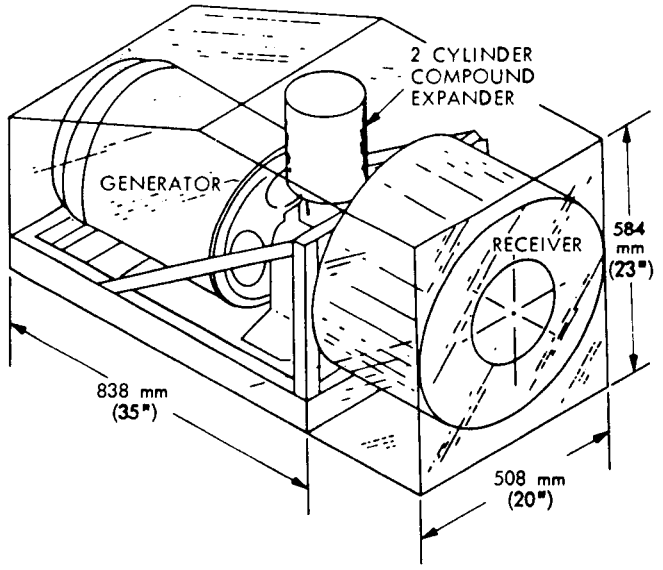
Steam Rankine Designs. The Rankine engines studied would require modest development to achieve goals for performance and lifetime (100,000 hours). The Sundstrand two-stage, reentry turbine (Figure 2-31a) would have required verification of a design life of 100,000 hours for bearing and seal designs and for overall operation at 730°C (1350°F). A Jay Carter Enterprises' reciprocating engine (Figure 2-31b) would have required development from their simple steam cycle operating at 540°C (1000°F) to the compound cycle designed under the study contract. This engine could be designed for a 30-year lifetime with major overhauls at 10-year intervals. The Foster-Miller Associates engine design (Figure 2-31c) used "counterflow" (versus uniflow in the Carter engine), which means that heat transfer between the inlet and exhaust must be essentially eliminated in order to achieve high performance. Additional modifications to the Foster-Miller design required to meet design goals were (1) the use of graphite rings to eliminate lubricating oil and (2) hydraulic operation of the valves.

Air Brayton Designs. The open- and closed-cycle Brayton engines designed by Garrett AiResearch were based on available engines in different development stages or on existing technology optimized to meet required performance. The Garrett open-cycle near-term (baseline) concept was a turbocompressor (Figure 2-32A) developed for a military generator for an auxiliary power (30-kWe) unit. The closed-cycle Brayton (Figure 2-32B) was based on a Pacific Fruit Express engine (15-20 kWe) to power a commercial transportation refrigeration unit. The second open-cycle unit (Figure 2-32C), an optimized turbocompressor based on technology developed for the Brayton Rotating Unit turbine (using gas bearings and an integral, permanent magnet alternator), would require more time to develop than the baseline design.

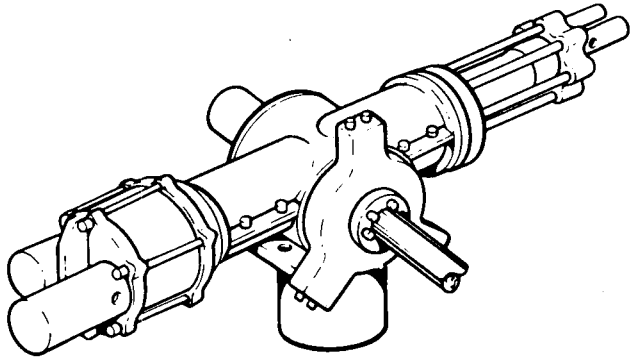
b. Steam Rankine-Cycle Engine. A simple Rankine-cycle steam engine was selected by the TPS Project for "solarization" and testing because it was the only available steam engine suitable for use with a small (6-m) parabolic dish. A 5-kWe single-cylinder steam engine (Figure 2-33) built by Jay Carter Enterprises was purchased by JPL in 1981 for use as a dish module power converter. Prior to this procurement, Jay Carter completed a preliminary design study based on one of their Rankine-cycle engines (with a two-cylinder expander) for this application. The study determined that for a 15-kWe engine/induction alternator unit, a single-cylinder expander was optimum for a simple cycle and two cylinders were optimum for a reheat cycle. Verification of this model through testing of the two-cylinder engine resulted



(a) Two-Stage Turbine
Sundstrand Energy Systems, Inc.



(b) Two-Cylinder Compound Reciprocating
Jay Carter Enterprises, Inc.



(c) Two-Cylinder Opposed, Compound Reciprocating
Foster Miller Associates, Inc.

Figure 2-31. Conceptual Steam Rankine Engine Configurations (see Reference 17)

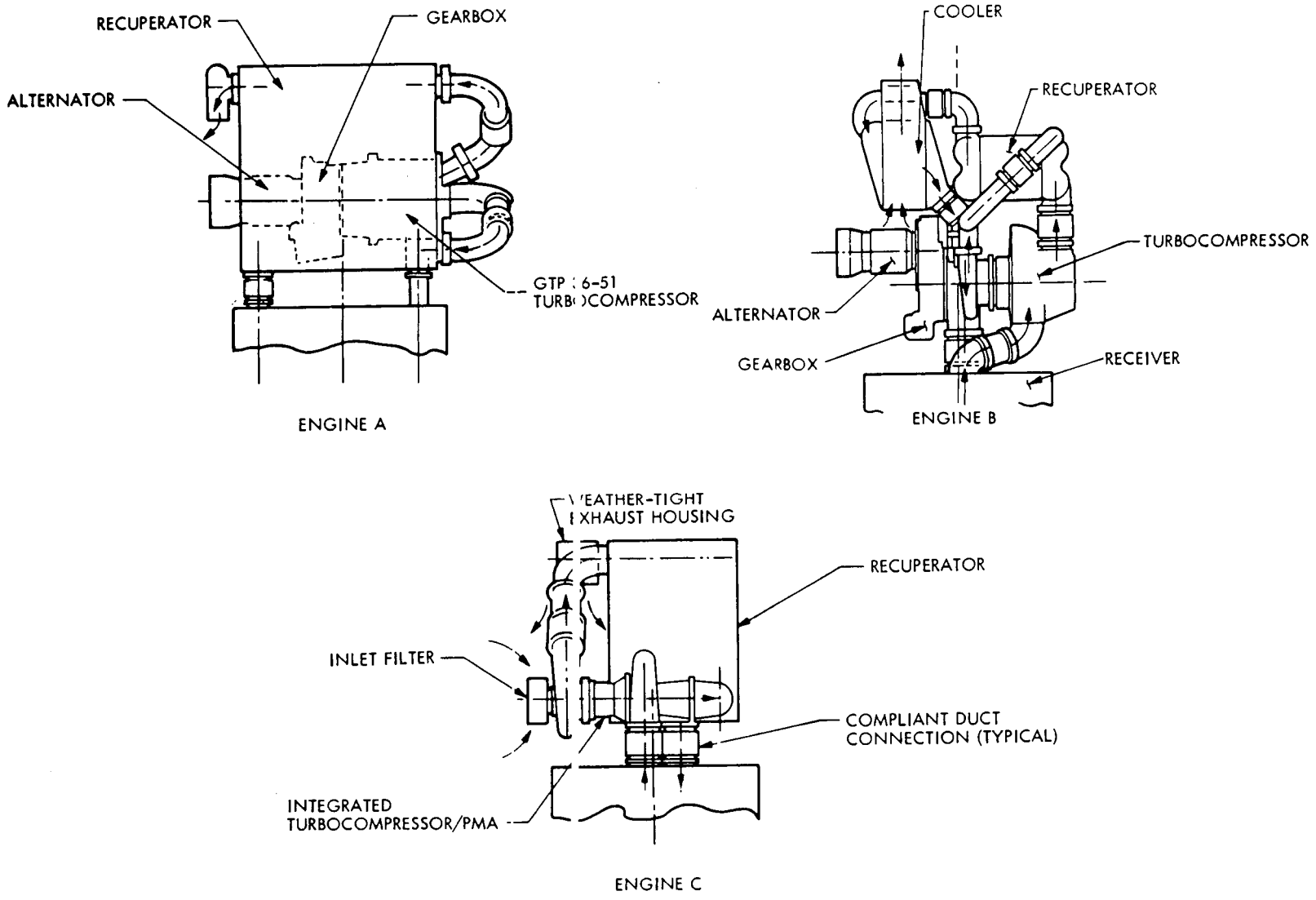


Figure 2-32. Conceptual Open- and Closed-Cycle Brayton Engine Configurations (see Reference 17)

Table 2-9. Conceptual Design Study Contracts of Rankine- and Brayton-Cycle Engines (see Reference 17)

Contractor	Engine	Working Fluid	Thermal Power Input, kWt	Inlet Temperature, °C	Inlet Pressure, MPa	Mass Flow, lb/h	Engine Efficiency, %
Sundstrand Energy Systems	Rankine, 2-stage turbine	Steam (reheat)	80	732	4.137	179	31
Jay Carter Enterprises	Rankine, compound reciprocating	Steam (reheat)	80	676	17.237	175	33
Foster-Miller Associates, Inc.	Rankine, opposed 2-cylinder reciprocating	Steam (reheat)	80	700	12.066	136	36
Garrett AiResearch	Brayton open-cycle (Fig. 2-32A)	Air	72.7	815	0.258	2226	30
Garrett AiResearch	Brayton closed-cycle (Fig. 2-32B)	Air	72.7	815	0.331	2443	30
Garrett AiResearch	Brayton open-cycle (Fig. 2-32C)	Air	72.7	815	0.269	2141	32

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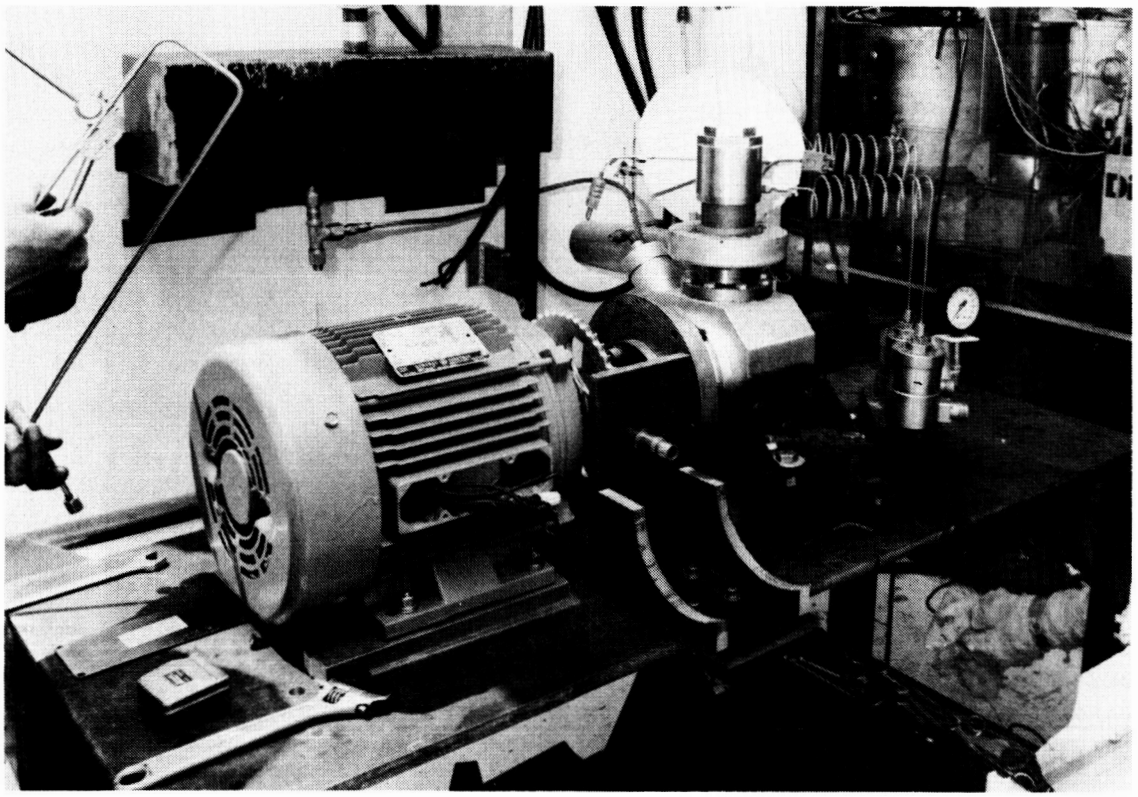


Figure 2-33. Carter 5-kWe Single-Cylinder Engine Under Test

in predictions of thermal-to-electric efficiencies of 26% for the simple cycle and 30% for the reheat cycle at an operating temperature of 677°C (1250°F) and a 15-kWe power level (Reference 52).

Solarization of the 5-kWe Carter engine required (1) modifying and refurbishing the piston, piston rod, and crankshaft; (2) machining a new cylinder head; and (3) replacing several small parts. Testing at the Parabolic Dish Test Site utilized a net concentrator aperture area of 87.6 m^2, a Garrett steam receiver, and a transport line to supply steam to the engine, which was located on the ground. A bypass valve was used to control steam conditions for these preliminary tests. Steam temperature was limited to approximately 399°C (750°F) and pressures to 7.7 MPa (1100 psi). Test results indicated a peak thermal efficiency of 12.7%, which is between 90 and 95% of the calculated efficiency for the engine operating at the reduced conditions of the test (see Reference 34). Therefore, the predicted thermal efficiency of this engine at peak steam design conditions of 566°C (1050°F) and 14 MPa (2000 psi) should be 12 to 15%, which is excellent for small, single-expansion steam engines.

c. Organic Rankine-Cycle Engine. The organic Rankine-cycle (ORC) power conversion unit was selected for first-generation dish-module applications because it had the potential for high efficiencies at moderate operating temperatures (around 400°C). Ford Aerospace and Communications

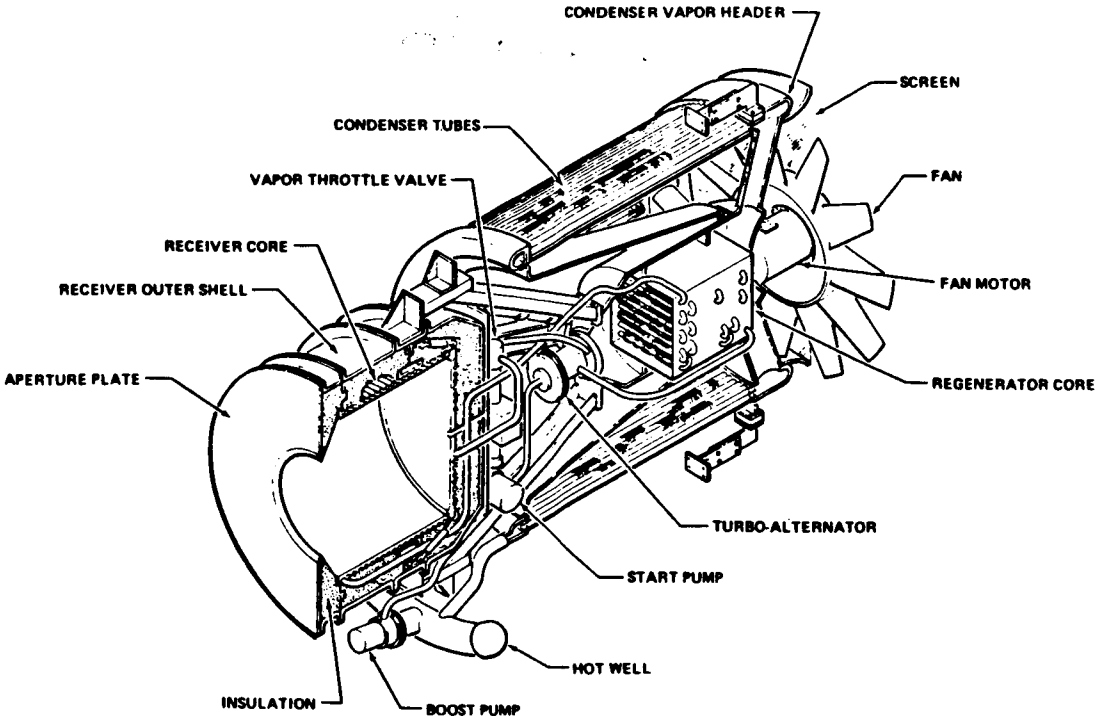
Corporation, the system contractor for the ORC module field experiment (see the Small Community Experiment described in Section III), subcontracted with the Barber-Nichols Engineering Company early in FY 1980 to design and fabricate an ORC engine assembly (see Reference 27).

Description. The ORC engine uses toluene as the working fluid at a maximum operating temperature of 399°C (750°F). Toluene ($C_6H_5CH_3$) yields high performance at lower temperatures and pressures than does steam. To avoid leakage and contamination of the working fluid, the ORC engine assembly is hermetically sealed (i.e., has no moving seals) with no external dynamic seals. The toluene lubricates the bearings, cools the alternator and pumps, and operates the hydraulic actuator of the control valve (Reference 53). The engine has a design power output of up to 20 kWe at rated conditions of 75.6 kWt input and 28°C (82°F) ambient air temperature and is designed to operate at all solar-related elevation angles from 5 to 90 deg above the horizon.

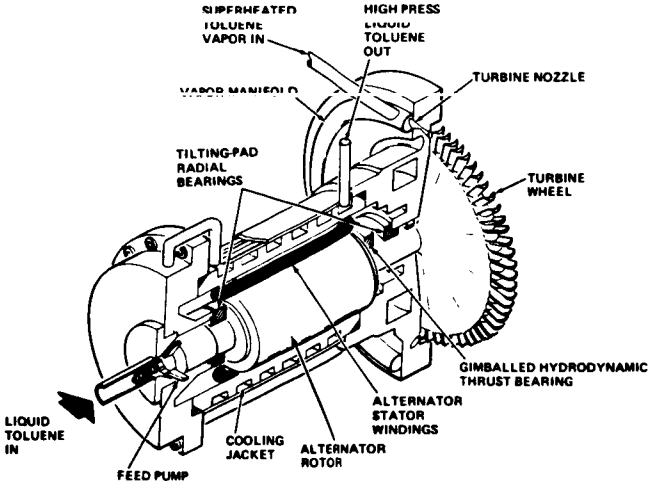
The complete ORC power conversion unit, shown in Figure 2-34, consists of the FACC organic receiver (described in Section II.B.4.c), the Barber-Nichols ORC engine assembly, and a permanent magnet alternator and rectifier by Simmonds Precision. The components of the engine assembly are a fan-driven, air-cooled condenser, a centrifugal feed pump, a regenerator (heat exchanger), and a single-stage axial flow turbine. The feed pump and turbine are mounted on the alternator shaft, which carries the permanent magnets and rotates at speeds between 50,000 and 60,000 rev/min. This high operating speed makes it possible for the turbine/alternator/pump assembly to be of a compact size and also allows the main feed pump to supply full system flow at pressures up to 5.9 MPa (855 psi) with a centrifugal impeller only 33 mm (1.3 in.) in diameter (see Reference 53).

During operation, the toluene flows in a closed loop and is expanded through the turbine. The exhaust vapor then passes through the regenerator to preheat the toluene entering the receiver then through the condenser and finally the pump. The permanent magnet alternator converts the mechanical output of the engine to high-frequency, three-phase alternating current (ac), which is converted to direct current (dc) by a ground-mounted rectifier. An inverter by Nova changes the dc output of the rectifier to three-phase, 60-Hz current at 480 V that can be fed directly into an electric utility distribution grid. Additional ground-mounted equipment includes the overspeed brake controller and relays.

Fabrication and Qualification Testing. Barber-Nichols fabricated the turbine wheel using an electrochemical machining technique and completed fabrication and testing of the condenser core, boost pump, and start pump prior to qualification testing of the engine/alternator/rectifier subsystem that took place in May 1981. The subsystem was tested at Barber-Nichols for 28 hours at elevation angles of 5, 45, and 90 deg (Figure 2-35). Efficiencies as high as 23.5% (net dc electric output divided by thermal input and accounting for parasitic losses) were demonstrated. The subsystem was then shipped to FACC and integrated with an electric resistance heater, receiver, inverter, and control system for testing that resulted in successful operation for 27 hours under stable operating conditions for steady-state,



POWER CONVERSION ASSEMBLY



TURBINE-ALTERNATOR-PUMP (TAP)

Figure 2-34. ORC Power Conversion Assembly with Detail of the Turbine/Alternator/Pump (see Reference 53)

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Figure 2-35. ORC Qualification Testing at Barber-Nichols

transient, cold and hot start-up, and normal and emergency shutdown modes at various thermal input levels. Grid-connected solar testing, begun in January 1982, is described below.

Solar Testing and Evaluation. The program for testing the ORC power conversion unit at the focal plane of a TBC at the Parabolic Dish Test Site (Figure 2-36) included determination of performance, stability, and efficiency in all operating modes as well as verification of subsystem compatibility (see Reference 29). On thermal input from the test bed concentrator, the ORC unit operated for a total of 33.6 hours at an insolation level of 950 W/m^2. Operation was smooth throughout the test series that included the following conditions: variable insolation levels and cloud passages, planned and random start-ups and shut-downs, various inverter input voltage settings, and all control modes. Measured outputs of the subsystems under test and the corresponding calculated efficiencies are shown in Figure 2-37. From a thermal input of 70.8 kW, the ORC engine/alternator/rectifier generated 16 kWe at an efficiency of 23% after accounting for parasitic losses (References 54 and 55).

In March 1982, the ORC test unit was removed from the TBC. Subsequent disassembly and inspection of the turbine/alternator/pump revealed three problems: (1) electrical arcing from the stator winding to the housing,

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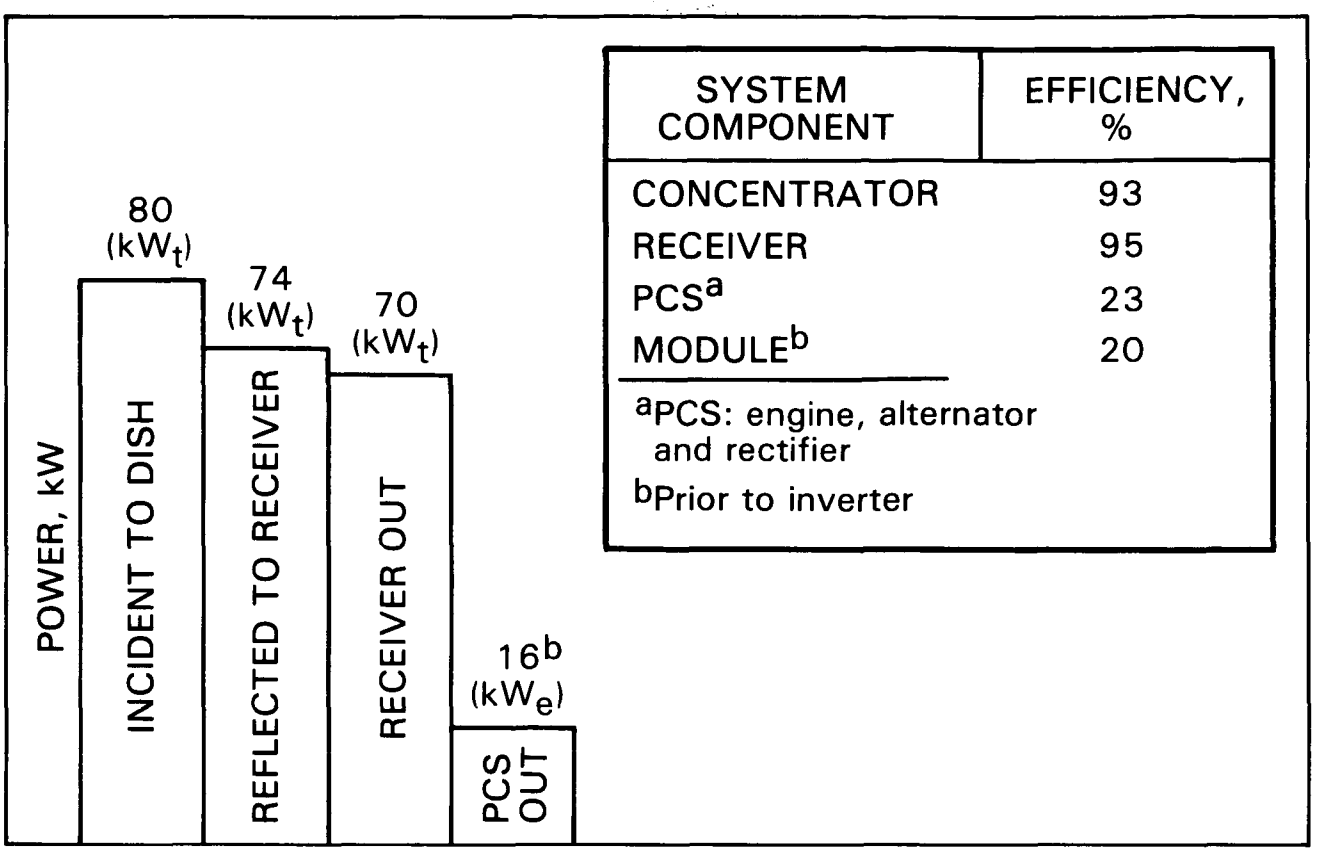
Figure 2-36. The ORC Receiver/Engine/Alternator Mounted on a TBC for Solar Testing



SYSTEM COMPONENT	EFFICIENCY, %
CONCENTRATOR	93
RECEIVER	95
PCS[a]	23
MODULE[b]	20

[a]PCS: engine, alternator and rectifier

[b]Prior to inverter

Figure 2-37. Measured Performance of the ORC Test Unit

(2) rubbing of the feed pump impeller, and (3) higher-than-predicted bearing wear. It also was discovered that alternator and feed pump efficiencies were lower than expected. The most promising method for increasing the alternator efficiency is to change the number of stator poles and to wire the armature portions in series instead of in parallel. Changes in the contour of the diffuser are expected to lessen performance problems caused by the feed pump.

An extensive test program was initiated to solve the problems of the internal arcing and of the excessive bearing wear. It was determined that the arcing was the result of inadequate quality control during fabrication and assembly. The bearing wear was finally diagnosed as being caused by a combination of rotor dynamic and electrodynamic effects. An externally fed, pressure-lubricated, five-pad Waukesha bearing solved the dynamics problem. Mounting this bearing in an electrically insulated carrier eliminated all detectable bearing wear. A successful 100-h "hot" test of the ORC power conversion system confirmed the effectiveness of these solutions (Reference 56).

d. Air Brayton-Cycle Engine. Open-cycle air Brayton engines offer higher efficiencies than the organic Rankine-cycle engine and also offer potential cost benefits from the automotive gas turbine development program being conducted at the NASA Lewis Research Center in conjunction with Garrett and Ford.

Early in FY 1980, a contract was awarded to the Garrett Turbine Engine Company for detailed design and fabrication of the baseline, open-cycle Brayton engine that was conceptualized under the study program described in Section II.C.3.a above. The concept subsequently was extended to include a fossil-fuel combustion capability for hybrid operation as well as coupling to the Sanders ceramic receiver described in Section II.B.4.f.

Description. The initial engine design used an existing turbocompressor from the Garrett GTP 36-51 gas turbine engine (Figure 2-38, Reference 57). The upgraded hybrid unit, however, is based on the Garrett automotive advanced gas turbine (AGT 101). The "solarized" version of the all-metal AGT, called the SAGT, operates on either solar and/or fossil-fuel thermal input using a hybrid combustor. Solar input to a Brayton receiver at 85 kWt heats the air from the recuperator [at 580°C (1075°F) and 0.25 MPa (37 psia)] to a temperature of 870°C (1600°F) for input to the turbine, which rotates at a speed of 80,000 rev/min. A mechanical drive reduces the speed to about 1800 rev/min to power a conventional electric generator. Under these conditions, the mechanical shaft output power of a production engine is estimated to be 15 kWe at an efficiency of about 32%. A later version of the SAGT using a permanent magnet alternator instead of a mechanical shaft drive is depicted in Figure 2-39.

The SAGT has the same internal configuration as the AGT 101, with the exception of two specially designed ducts that channel the air flow between the engine and the Sanders receiver and allow for thermal expansion. Engine controls using a microprocessor were easily modified for performing necessary

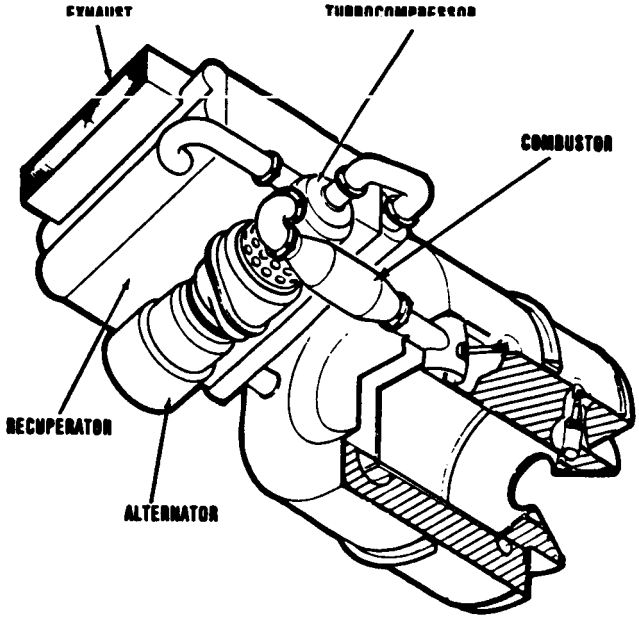


Figure 2-38. Initial Garrett Air Brayton Engine Concept Based on the GTP 36-51 Gas Turbine

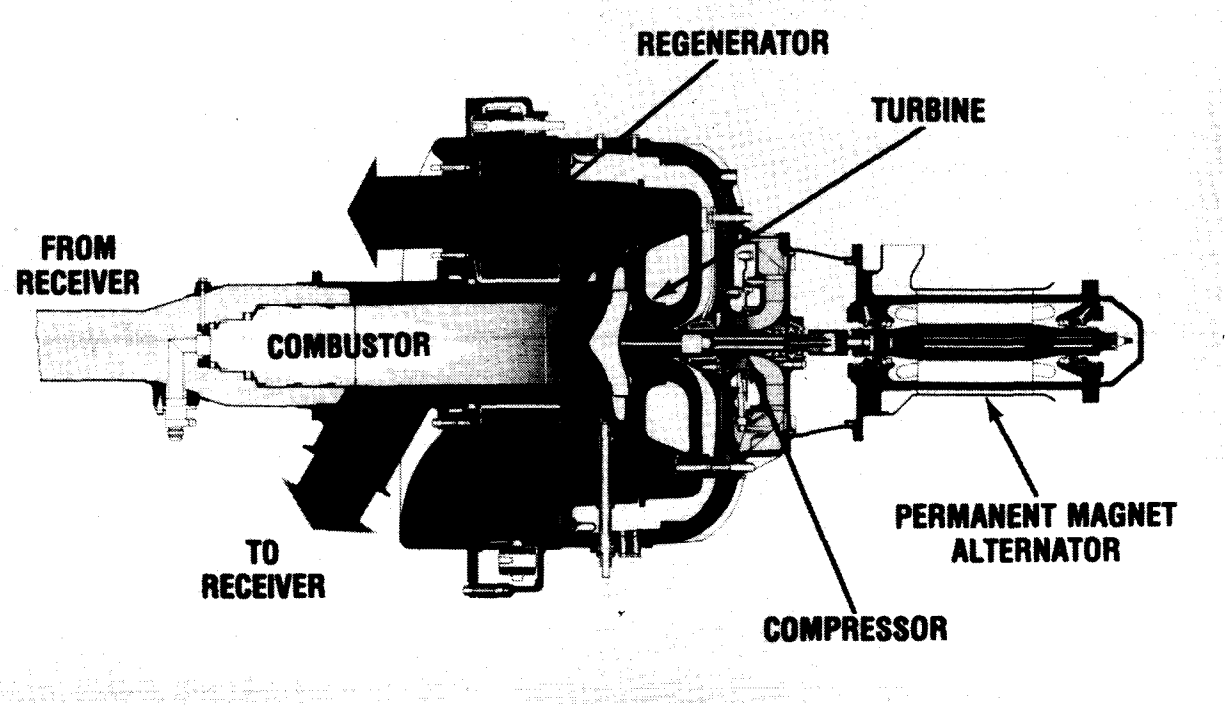


Figure 2-39. Conceptual Drawing of the Garrett Solarized Advanced Gas Turbine Based on the AGT 101

solar operational requirements. The induction generator is a commercially available, high-efficiency, 60-Hz unit that can be connected directly to the ac grid, thus eliminating the need for a separate power conditioning unit (Reference 58). Assembly of the SAGT power unit with a Sanders receiver was completed in July 1982 and is shown in Figure 2-40.

Test and Evaluation. Bench testing late in 1982 of the metal AGT included runs to 100,000 rev/min under load and pointed to the following development problems: (1) interference on re-start due to thermal expansion caused by soak back, (2) intermittent dynamic stability problems from 75,000 to 100,000 rev/min, and (3) excessive leakage in the rotating ceramic regenerator seals and in other joints. Solar testing of the SAGT/ receiver unit on a test bed concentrator are planned when these problems have been adequately resolved (see Reference 30).

Future Plans. Late in FY 1981, JPL planned a systems contract for design and integration of a parabolic dish-electric module that would incorporate the SAGT as the power conversion unit (see Reference 30). This contract was not awarded at that time because another Brayton engine (the subatmospheric engine described below) was chosen for incorporation into an experimental dish-electric module. However, testing of the SAGT was resumed in 1985 (see Section III.C).

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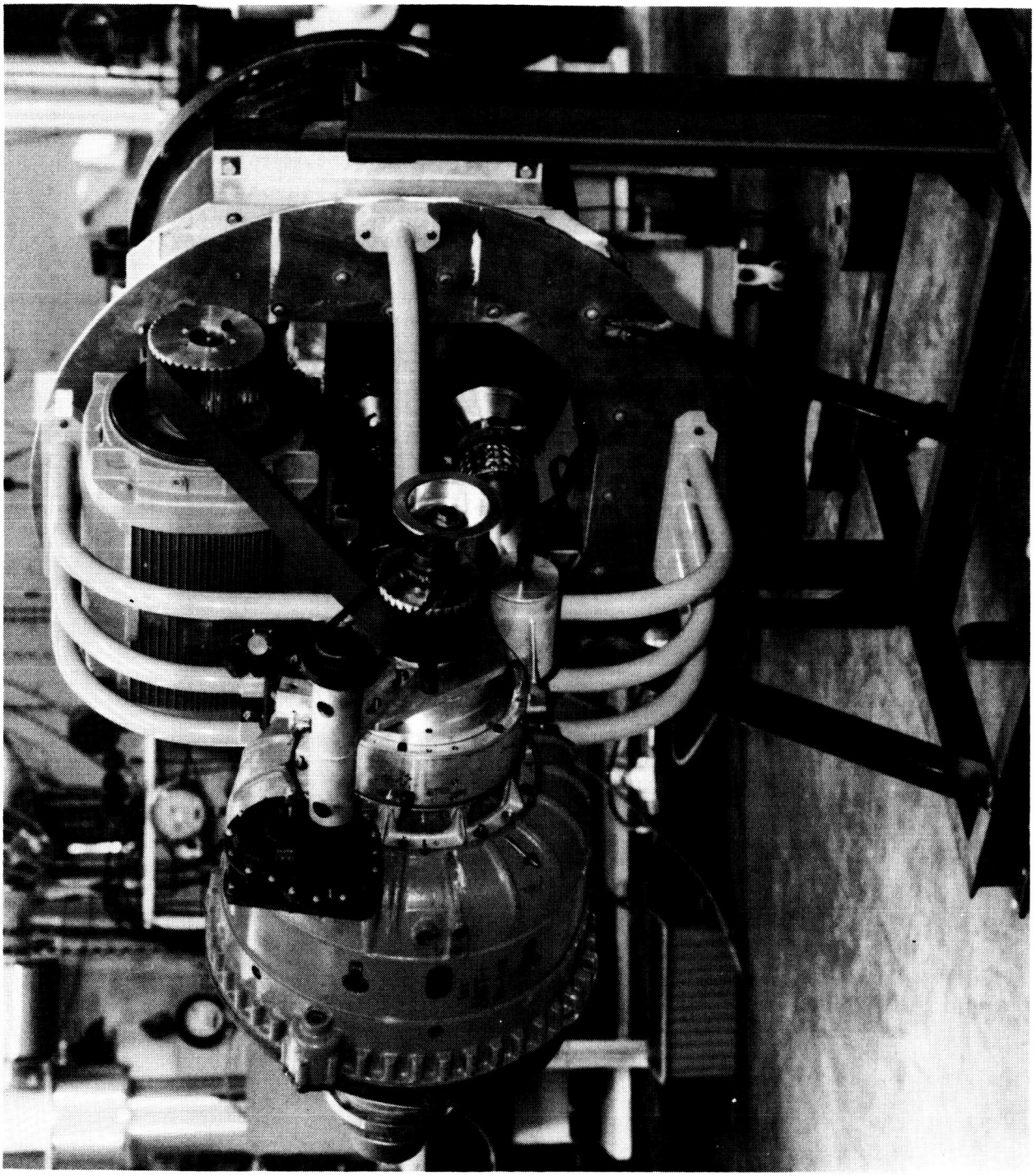

Figure 2-40. Garrett Solarized Advanced Gas Turbine/Sanders Receiver Test Unit

Second-generation versions of the SAGT incorporating ceramic parts are thought to be capable of turbine inlet temperatures up to 1370°C (2500°F). The shaft power of such engines has been estimated to be as high as 71 kWe at efficiencies up to 48% (see Reference 29). SERI's work on the technical feasibility of ceramic materials for an all-ceramic gas turbine (Brayton) engine is described in Reference 3.

e. Subatmospheric Brayton-Cycle Engine. A gas-fired heat pump system, developed by the Garrett AiResearch Manufacturing Company for the Gas Research Institute, features a subatmospheric Brayton-cycle (SABC) engine (Figure 2-41) driving the centrifugal compressor of a reversible vapor-compression heat pump. As part of the JPL dish project, an SABC engine was adapted by Garrett for use in a dish-electric module. In the solarized subatmospheric engine, air is heated in a solar receiver to a temperature of 870°C (1600°F) at ambient pressure, passes first through the turbine, is cooled by the recuperator, and drawn into the vacuum created by the compressor. The air is then compressed (back to ambient pressure), passed through the recuperator again, and then returned to the receiver for heating.

Late in 1981, a contract was initiated with Sanders Associates to design and integrate a dish module consisting of a concentrator, air receiver, and Brayton-cycle gas turbine engine (see Reference 36). The baseline subsystem being planned uses a Garrett recuperated subatmospheric Brayton engine, a Sanders ceramic air receiver, and a LaJet dish concentrator.

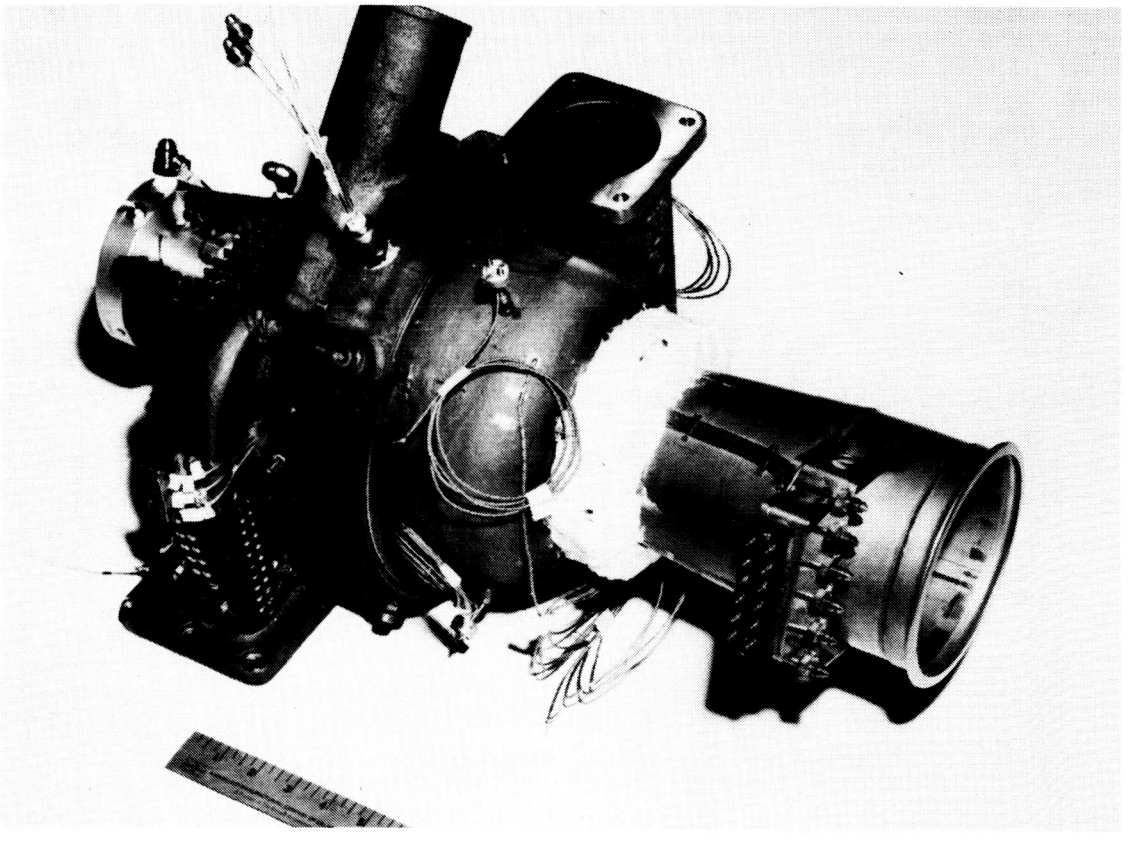

Figure 2-41. Subatmospheric Brayton-Cycle Engine

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At the beginning of 1984, the unimproved SABC Mod IIIA engine was assembled, bench tested, and qualification fuel tested at Garrett AiResearch. These preliminary tests indicated low performance, but it is not clear whether this was due to the engine itself, the passive solar receiver used for testing, the load cell permanent magnet alternator, or the test calibration (Reference 59). In April 1984, the Mod IIIA engine was delivered to Sanders Associates for integration into the Brayton developmental test module as described in Section III.

f. Stirling-Cycle Engine. The decision to modify a Stirling-cycle engine for second-generation dish application was based on the engine's high efficiency and reasonable cost (Reference 60). In 1980, JPL awarded a contract to United Stirling AB of Sweden (USAB) to modify a Stirling engine for use in a dish-electric module. Their Model 4-95 was found to be the ideal choice because its thermal energy requirement is 65 kWt, which is consistent with the established baseline design for the Stirling engine subsystem based on a 10-m-diameter concentrator with a focal length of 0.6.

Description and Modification. The USAB Model 4-95 Solar Mk I engine (shown in Figure 2-42 with an integral receiver) is a four-cylinder (95-cm^3 displacement per cylinder), double-acting kinematic machine with a drive shaft and two crankshafts. Throughout 150,000 hours of testing on 16 unmodified engines, the 4-95 was found to be clean, efficient, and durable. A new rod seal, a critical element, demonstrated high reliability with no failure modes (Reference 61).

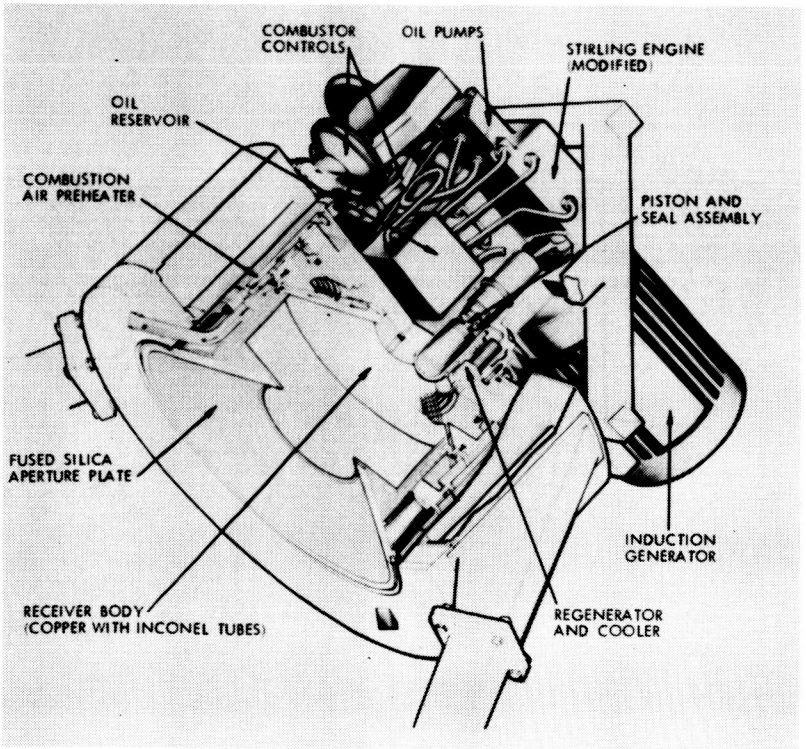

Figure 2-42. USAB Stirling Engine with Integral Receiver

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Modifications to the 4-95 for solar use are necessary principally because of the inverted operating position required. Changes to the lubrication system included machining numerous holes to form oil drainage passages in the crankcase bulkheads and gas compressor housing to provide adequate drainage by gravity alone. To further assure "dry sump" operation under dynamic conditions, an external scavenging pump was installed with an external pressure lubrication pump adjacent to it. An external oil tank was installed below the lowest drainage point and connected to the crankcase outlets by short pipes. USAB also attached a General Electric induction alternator to the engine and fabricated a steel frame for mounting the engine/alternator to a test bed concentrator (Reference 62).

Testing in the Inverted Position. Early in 1981, testing of the 4-95 Stirling engine in the inverted position using helium as the working fluid took place at USAB in Sweden (Figure 2-43). Under simulated dish module orientation, the engine operated successfully for a total of 350 hours at 1500 rev/min with a heater-head temperature of 710°C (1310°F) and a coolant temperature of 50°C (122°F). The maximum power output was 22 kWe at an overall efficiency of 31.5%. Minor problems that occurred during testing with oil flow were solved by increasing the drainage pipe area. It was also determined that the piston rod sliding seals were capable of functioning well in the inverted position (see Reference 62). In June 1981, the Stirling engine/alternator was coupled to the Fairchild hybrid receiver (described in Section II.B.4.d) then shipped to the PDTS for solar testing.

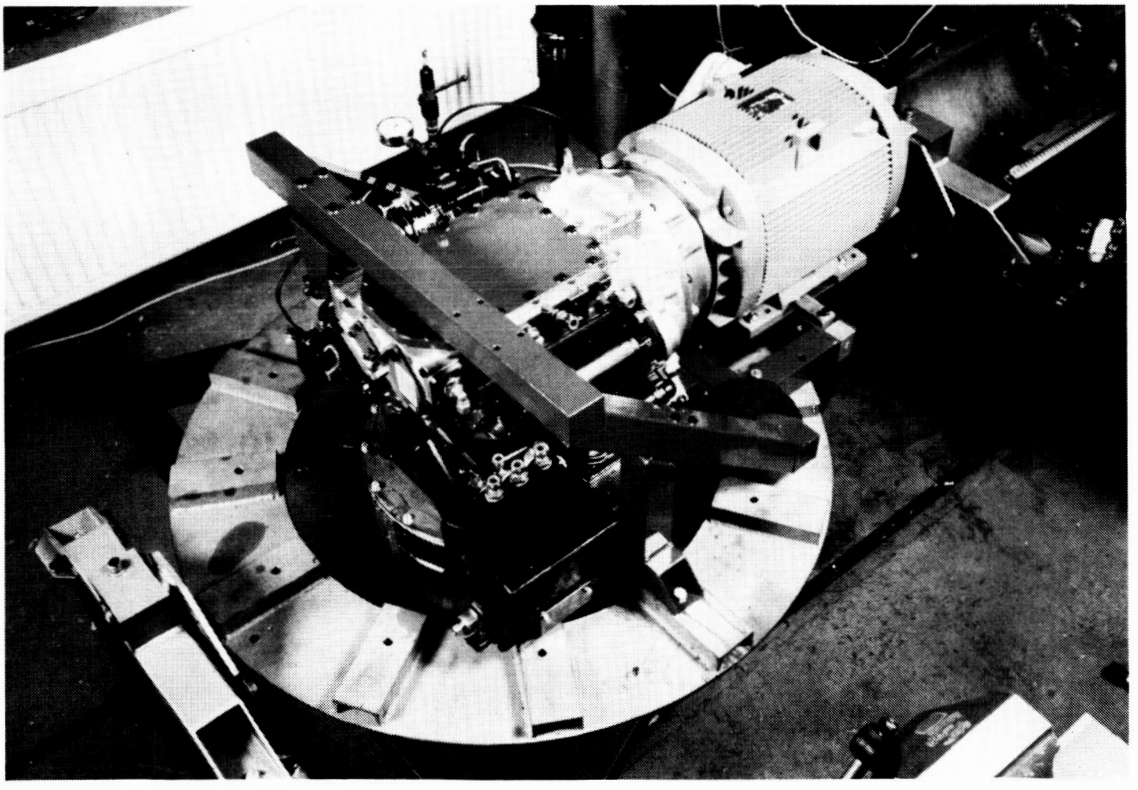

Figure 2-43. Bench Testing of Stirling Engine/Alternator in Inverted Position

Hybrid and Solar Testing. Upon its arrival at the solar test site, initial tests were conducted on the Stirling engine/receiver unit by Advanco Corporation, the system integrator, prior to concentrator mounting. Personnel from JPL, USAB, and Advanco installed the Stirling test unit on a TBC for hybrid operation at heater-head temperatures of up to 770°C (1420°F), mean engine pressures to 11 MPa (1625 psia), and solar thermal inputs to 20 kWt using only 25% of the TBC mirror facets. After generating 15 kWe, brazing failures in the heater head precluded further testing of the unit in the hybrid mode.

Solar testing of the Stirling engine continued using five similar USAB experimental solar-only receivers (see Section II.B.4.g). During a series of sunrise-to-sunset tests using hydrogen as the working fluid (Figure 2-44), the power output was in excess of 25 kWe at an insolation level of 1000 W/m^2, resulting in a solar-to-electric conversion efficiency of 29%, not accounting for parasitic losses. The electricity generated was fed directly into the Southern California Edison Company distribution grid at 60 Hz and 480 V by the induction alternator, with no special power processing required. Measured performance of the Stirling engine resulting from a range of solar tests is summarized in Figure 2-45.

Future Plans. During 1983 and 1984, Advanco Corporation fabricated and tested a Stirling module (consisting of the 4-95 Mk II Solar SE, and a receiver and concentrator by Advanco) as the result of a DOE Program Opportunity Notice. This Stirling module development program is discussed in Section III.

Late in 1983, McDonnell Douglas Corporation entered into an agreement with United Stirling AB of Sweden to purchase 4-95 Mk II engines for the purpose of mass producing dish-electric modules for the near-term market. Their progress is also discussed in Section III.

4. Engine Technology Assessment Summary

A number of heat engines have been tested at the PDTS to help ascertain their readiness for widespread deployment by better understanding their performance and operating and maintenance (O&M) costs. Engines tested included three steam engines (two Carters and the Omnium-G), the Barber-Nichols organic Rankine-cycle engine, and the USAB Stirling-cycle engine. While not tested by JPL at the PDTS, two Brayton-cycle engines (the solarized advanced gas turbine manufactured by the Garrett Turbine Engine Company and the subatmospheric Brayton-cycle engine built by Garrett AiResearch Manufacturing Company as well as a fourth steam engine (the Bank engine from the United Kingdom)[5] were included in the JPL engine assessment program. All of these engines were run successfully, yielding considerable performance data and some O&M figures. As might be expected, each of these engines showed strengths and weaknesses that, when combined with the large uncertainties in their mass production costs and particularly their long-term

[5]Built by David D. Banks, 681 Preston Old Road, Feniscowles, Blackburn BB2-5EN, Lancashire, England.

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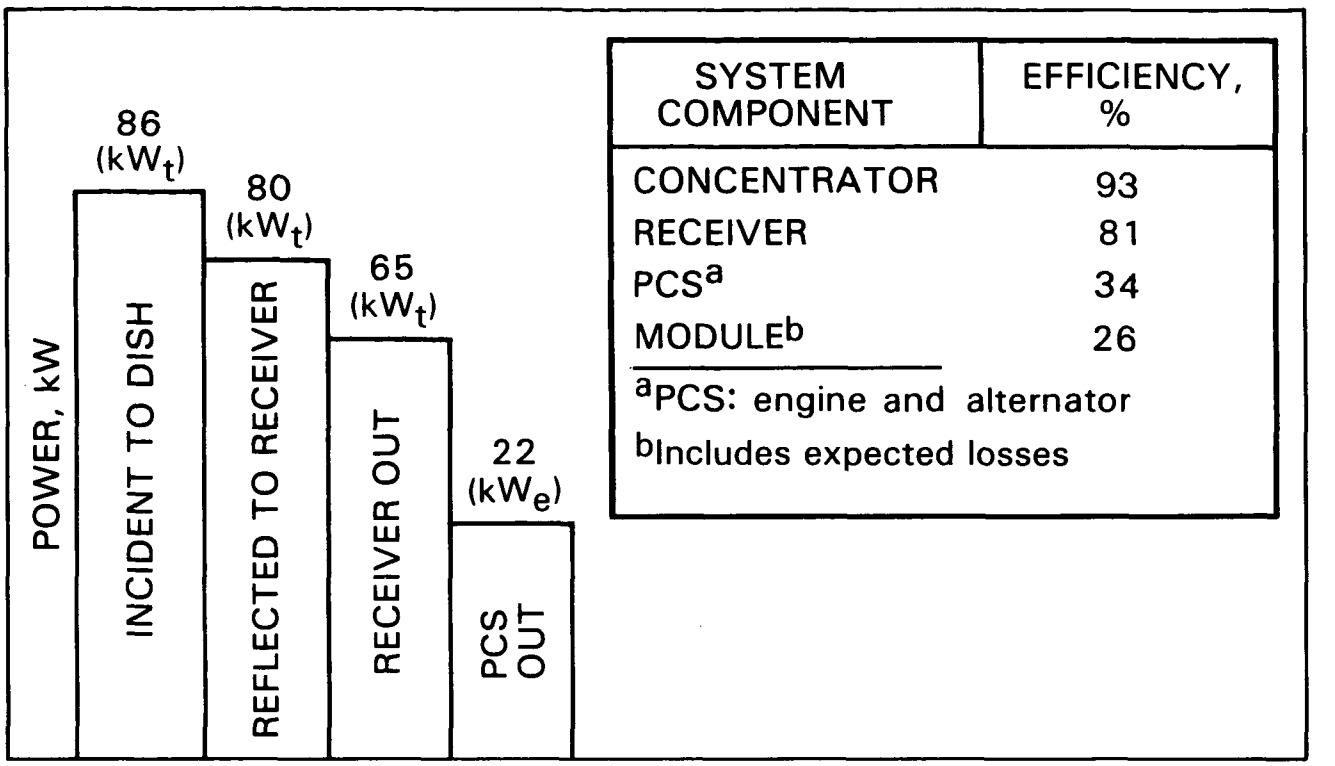
Figure 2-44. Stirling Engine Generating Electricity at the TBC's Focal Plane



SYSTEM COMPONENT	EFFICIENCY, %
CONCENTRATOR	93
RECEIVER	81
PCS[a]	34
MODULE[b]	26

[a]PCS: engine and alternator

[b]Includes expected losses

Figure 2-45. Stirling Measured Performance (Receiver efficiency is an estimated value)

O&M costs, make the clear choice of a single winner impossible. Efficiencies were as expected, with the Stirling engine the highest (regularly near 40% for the engine only), the ORC and Brayton in the mid-20% range, to the small steam engines in the teens. But even with this rather clear range of performance known, the final economic outcome is still uncertain until enough long-term O&M data can be gathered to assess plant operating costs and until pilot-scale rather than the current hand-built prototype production costs are developed. However, the pioneering work done thus far clearly demonstrates the technical feasibility of the small heat engine as a solar power conversion device and strongly indicates that continuing work will demonstrate the economic viability of this type of engine for many applications.

D. ENERGY STORAGE

The use of storage with parabolic dish-electric power plants can greatly reduce the problem of mismatch between the outgoing power produced solely from insolation and the electric power demanded by users (Figure 2-46). Hybrid modules, operating from both solar and fossil fuel, can provide a more even match between supply and demand. Or, a dish-electric plant may not require storage when connected to a conventional plant via a distribution grid. The conventional plant modulates its output so that the solar plant provides fuel displacement (but not capacity displacement). In this case, the conventional plant would take the place of a storage system (Reference 63).

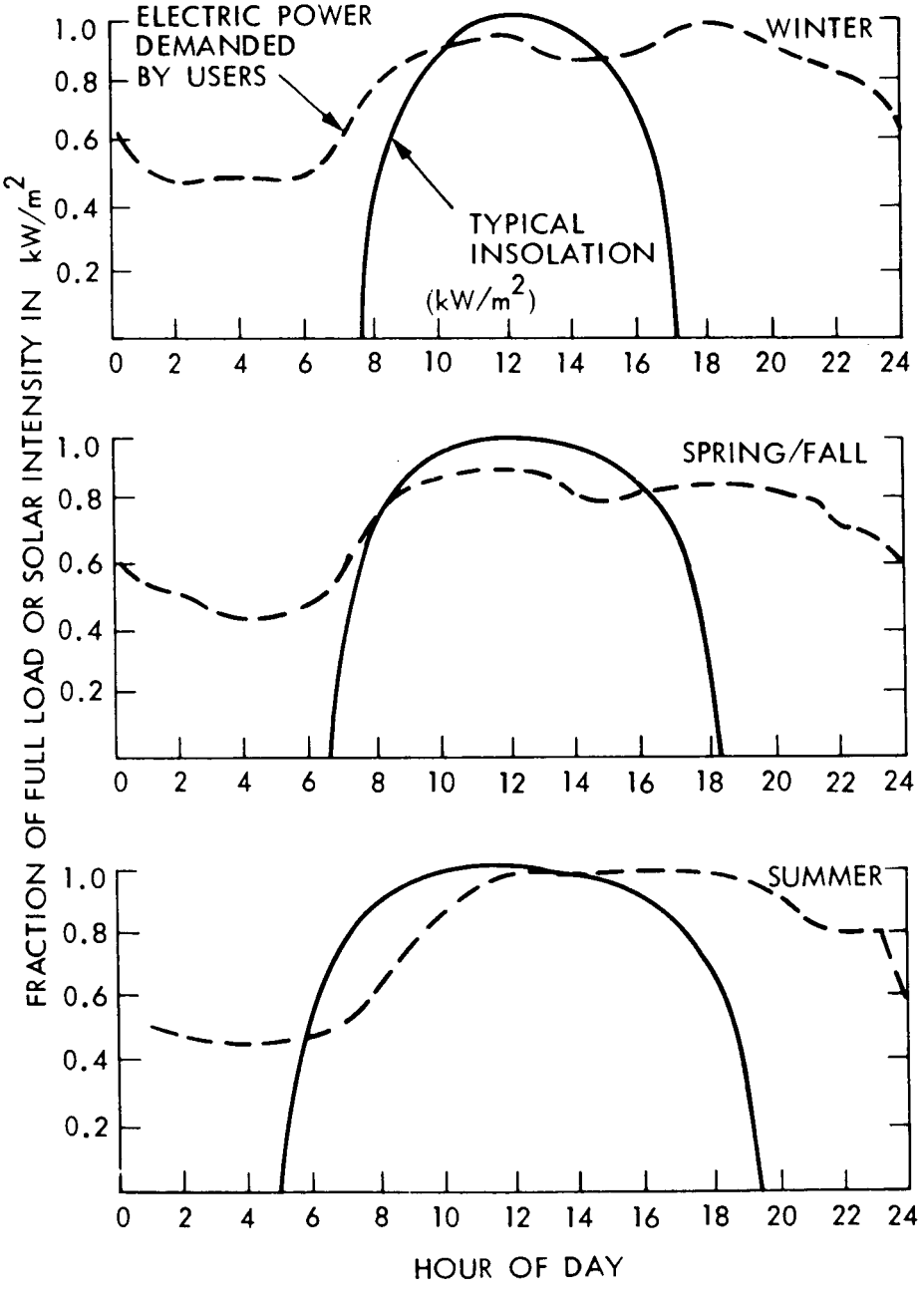


Figure 2-46. Insolation Versus Demand Load (see Reference 63)

To date, the many types of storage considered by the JPL TPS Project can be classified as either focal-mounted or ground-mounted. Focal-mounted storage is usually called buffer storage and is integrated with the solar receiver. Ground-mounted systems include battery (electrochemical) storage, thermal storage using large external tanks, and thermochemical storage (see section on thermochemical transport and storage, p. 2-75). A dish power plant could employ hybrid modules as well as a combination of focal- and ground-mounted storage systems. Determination of the storage modes to be used for a particular plant would depend on site-specific factors that include demand, rate structure, and cost of capital. A methodology for evaluating the cost effectiveness of a thermal storage system for a specified solar power plant with a given demand profile is described in Reference 64.

1. Buffer Storage

Buffer storage helps provide a constant heat input to the engine and also minimizes the number of start/stop cycles, thus extending engine life, improving engine efficiency, and reducing control requirements. Each type of power conversion unit would require a different amount of thermal buffering to handle short-term (1 hour or less) variations in solar flux. During 1979 and 1980, the TPS Project awarded contracts to General Electric, Ford Aerospace and Communications Corporation, and Garrett AiResearch for the purpose of evaluating latent-heat buffer storage systems for the Stirling-, Rankine-, and Brayton-cycle engines, respectively.

In a related contract, a heat pipe solar receiver concept by GE (described in Section II.B.4.e) that incorporates latent heat thermal energy storage was demonstrated during modular testing on a full-scale (2.5-cm, 1-in.-diameter) heat pipe and three full-scale (5.1-cm, 2-in.-diameter) thermal storage containers. The following conclusion was drawn from the testing: In this design, heat pipe thermal transport and latent heat storage provide a near-isothermal and self-regulating heat source for stable operation of solar-powered engines (Reference 65).

In-house efforts to develop latent heat buffer storage included (1) an investigation of candidate salt-containment combinations (shown in Table 2-10) and (2) the formulation of a computer program to simulate a parabolic dish receiver having buffer storage capability.

Of the candidates listed in Table 2-10, the phase-change material selected for a detailed system study was $NaF-MgF_2$ (66.9%-33.1% by weight) eutectic salt mixture. The analysis assumed use with a Stirling power converter with an output of 25 kWe at an insolation of 1.0 kW/m^2. Preliminary results indicated that the heat transfer characteristics within the phase-change material (PCM) and at the PCM/solid surface interface are critical factors affecting subsystem performance and that the effects become more severe as the storage capacity increases. It was also shown that these effects can be alleviated by PCM heat transfer enhancement techniques such as the use of fins, bulk additives, mini heat pipes, metallic meshes, and screens (Reference 66).

Table 2-10. Candidate Storage Media for Dish-Mounted Receivers (see Reference 27)

Application	Temperature	Salt Composition by Weight %	Melting Point	Containment Material
Rankine	427-454°C (800-850°F)	61 KCl-39 $MgCl_2$	436°C (816°F)	316 & 321 SS Cr/Mo alloy steel
Steam Rankine	538-566°C (1000-1050°F)	25.9 Na_2CO_3-38.8 NaCl-35.3 NaF	557°C (1035°F)	316 & 321 SS Cr/Mo alloy steel
Brayton, Stirling	802-728°C (1475-1525°F)	66.9 NaF-33.1 MgF_2	813°C (1495°F)	316 & 321 SS
Brayton, Stirling	788-829°C (1450-1525°F)	75 NaCl-25 NaF	795°C (1463°F)	321 SS
Brayton, Stirling	802-829°C (1475-1525°F)	100 NaCl	802°C (1475°F)	9 Cr/1 Mo alloy steel

A computer model, called High Temperature Energy Storage (HTES), predicts the performance of the receiver under varying solar flux, ambient temperatures, various amounts of latent-heat buffer storage, and different thermal control techniques (see Reference 27).

2. Battery Storage

Surveys conducted by the Project in 1981 showed that existing battery manufacturers would be able to produce enough capacity by 1990 for several solar thermal power plants (see Reference 63). The battery systems for these plants would include a bidirectional converter/inverter to couple the system to the distribution grid (Figure 2-47). The 16 battery types evaluated by the Project are listed in Table 2-11 and discussed in detail in Reference 67. The results of the study showed that lead-acid and Fe-Cr Redox batteries are the most attractive storage systems for use with dish-electric power plants. The specific type of lead-acid battery suitable for solar thermal applications is one that is designed for repetitive, deep discharges of 5 to 10 hours on a daily basis at moderate to high power densities. Advanced lead-acid batteries now being developed for utility and electric vehicle applications are expected to cost less and provide better performance than batteries now in use (see Reference 27).

3. Thermal Energy Storage

Large thermal energy storage systems for solar thermal power plants are being studied and evaluated under the DOE Central Receiver Program

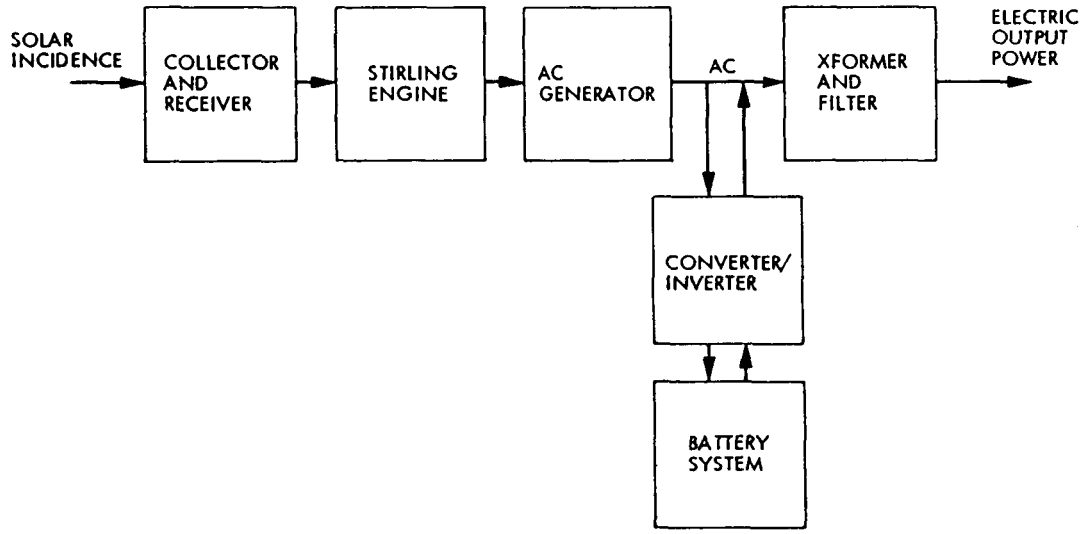


Figure 2-47. Battery Storage System for a Dish-Electric Power Plant Using an Ac-Link Transport Approach (Reference 68)

managed by Sandia National Laboratories-Livermore (SNLL) (Reference 69). In 1975, Sandia developed storage systems for both 10- and 100-MWe water/steam-cooled central receiver power plants. As a result of these studies, research experiments were performed on two systems: (1) a 1.6 MWt-h two-stage sensible heat storage system using oil and Hitec (an inorganic nitrate salt) and (2) a 4-MWt-h storage system that works on the thermocline principle using oil and rock/sand in a single tank. The latter was chosen for the 10-MWe Central Receiver Pilot Plant that is operating near Barstow, California. The pilot plant storage system operates over a temperature range of 218 to 304°C (425 to 580°F) and can deliver up to 7 MWe over a 4-h period. SNLL identified the following as promising storage applications: (1) a latent heat storage unit that can be integrated with a saturated steam receiver and (2) a process heat system requiring saturated steam.

According to SNLL (see Reference 69), high-temperature storage [815°C (1500°F) and above] for use with central receiver plants employing Brayton or Stirling engines would require new system configurations and low-cost containment approaches. Studies conducted by the TPS Project identified a molten salt (NaOH) storage system as an attractive candidate for high-temperature (815°C) dish applications (see Reference 63).

A storage concept consisting of a cluster of dish collectors supplying heat (up to 815°C, 1500°F) to ground-based thermal storage and power conversion units was analyzed at JPL (Figure 2-48) (Reference 70). In this study, three sensible heat systems [molten salt (NaOH), liquid sodium, and checker stone (discussed in next paragraph)] and one latent heat system [molten salt ($NaF-MgF_2$)] were paired with Stirling and Brayton engines for

Table 2-11. Cost and Performance of Advanced Electrochemical Storage Batteries (see Reference 27)

Battery Type	Initial Cost[1]	# Cycles At 80% DOD	Battery Efficiency%	Throughput Efficiency%[4]	Projected Availability	Probability of Availability[2]
Adv. Pb-Acid	$116-$130/kWeh	4000	80-85	73-78	1985	0.95
Na-S (FORD)	$43/kWeh	2500	76	70	1985	0.95
Na-S (FORD)	$43/kWeh	2500-5000	75	69	1985	0.80
Na-S (DOW)	$33/kWeh	3000	90	83	1990	0.20
Fe-Cr Redox (LeRC)	$132/kWe + $22/kWeh	10000	75	69	1990	0.80
$Zn-Cl_2$ (EDA)	$59/kWe + $27/kWeh	2500-3500	71-74	65-88	1985	0.95
(Argonne)	$54/kWeh	3000	85	78	1990	0.70
$Zn-Br_2$ (Gould)	$49-$59/kWeh	2500	70	65	1990	0.70
$Zn-Br_2$ (Exxon)	$32/kWeh	2500-5000	80	74	1990	0.70
$Zn-Br^2$ (GE)	$58/kWeh	2000	75	69	-	-
Fe-Air (Westg)	$32/kWeh	1000	50	46	1985	0.60
Ni-Fe (Westg)	$54/kWeh	2000	60	55	1985	0.70
Ni-Fe (EP)	$65/kWeh	2000	65-70	60-65	1990	0.70
$Ni-H_2$ (ERC)	$65/kWeh	10000	60-70	55-65	1990	0.20
Ni-Zn (Gould)	$108/kWeh	2000[3]	90	83	1985	0.60
H_2-Cl_2 (BNL)	$81/kWeh	-	65	60	-	-

[1]Updated to mid-1979 dollars: costs are based on 80% depth of discharge (DOD) and are for battery only (not Balance of Systems). Also batteries are overdesigned so that they will deliver full rated capacity at end of indicated number of cycles.

[2]Predicated upon EPRI data, vendor data, and best engineering judgment

[3]40% DOD

[4]Throughput efficiency (product of battery and inverter/converter efficiencies)

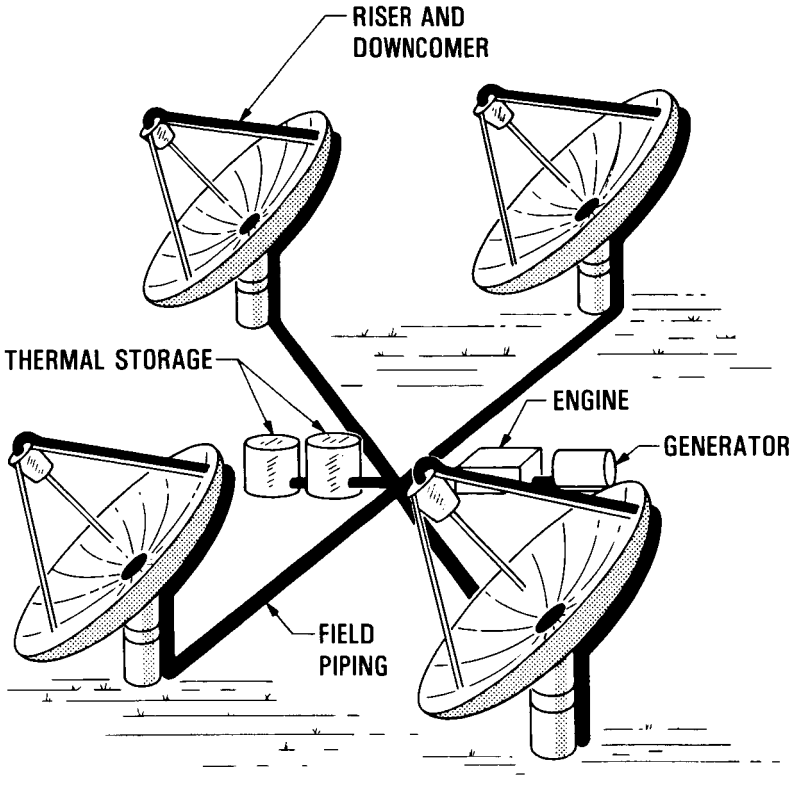


Figure 2-48. Thermal Storage Concept for a Cluster of Dish Collectors

detailed examination as 6-hour storage devices. Based on the achievement of energy costs in the same range as that of dish battery systems [i.e., Redox (FeCr), sodium sulfur, zinc chlorine, and zinc bromine], the following thermal storage systems are the most promising for dish cluster arrangements: (1) sensible heat systems employing molten-salt (sodium hydroxide) storage and transport for use with either Brayton or Stirling engines, and (2) latent heat systems using (a) an engine-powered (Stirling) concept of direct contact, scraped tube, passive, and polished tube and (b) a direct-contact Brayton concept.

A unique storage concept developed by Sanders Associates under contract to JPL is the "checker stove" -- similar to a scaled-down version of large storage/regenerator systems used in the glass and steel industry. The solar checker stove, designed for use with a gas turbine engine, uses cordierite ceramic honeycombs as the storage material (see Reference 7).

E. TRANSPORT

Transport systems for parabolic dish power plants are of three types: thermal, thermochemical, and electric. Thermal transport systems carry heated transfer fluid from a field of dish collectors (with distributed, focal-mounted receivers) to a ground-mounted turbine/generator for electricity production or directly to the point of use requiring process heat (Figure 2-49).

Thermochemical transport is a type of thermal transport where energy is absorbed in the receiver using an endothermic reaction, transported to its point of use at lower temperatures, then released by an exothermic reaction. An electric transport system collects electricity from dish modules (with distributed, focal-mounted engine/receiver units), processes it as required, and delivers it to the load (Figure 2-50).

1. Thermal Transport

During 1980 and 1981, the TPS Project examined cost-effective thermal transport for dish collectors. Earlier studies had shown that transport losses from networks (including pumping requirements and thermal losses) using hot water (93°C, 200°F) and steam (510°C, 950°F) were generally less than 10% of the total output of a field of collectors producing up to 30 MWt. Optimized, low-cost transport systems, achievable through automated factory fabrication and semi-automated field installation, would cost 45% less than systems built using conventional labor-intensive techniques. Transport losses from these optimized systems would also be less than 10% even up to plant sizes of 100 MWt (see Reference 5).

A computer optimization code was developed at JPL to evaluate thermal transport concepts and to determine the most cost-effective thermal transport layout. The code incorporated data on dish collector spacing, operating temperatures, heat losses, fabrication techniques, pumping losses, and costs (see Reference 29).

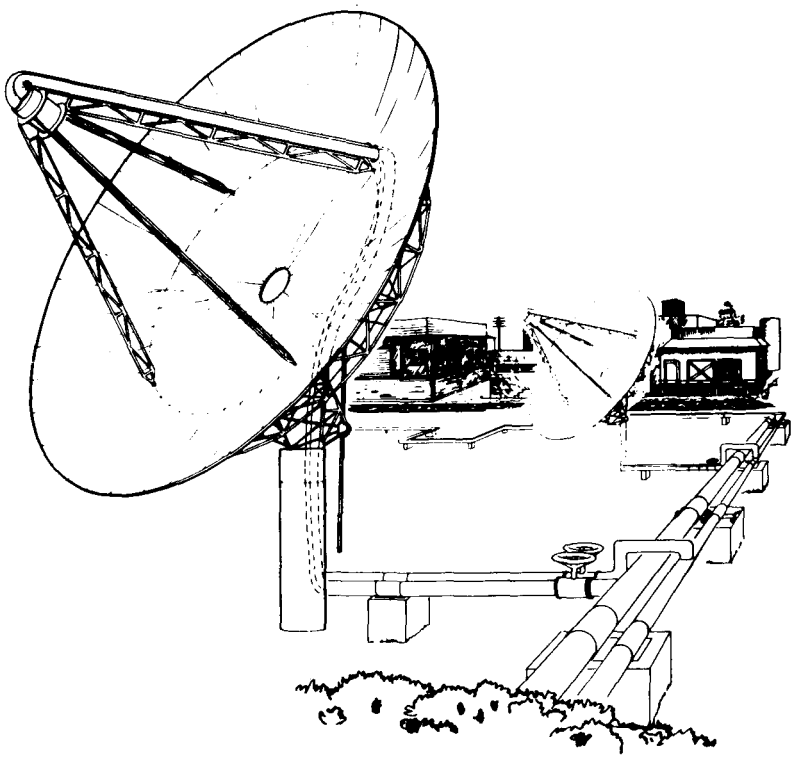


Figure 2-49. Artist's Concept of a Dish Collector Thermal Transport System (see Reference 5)

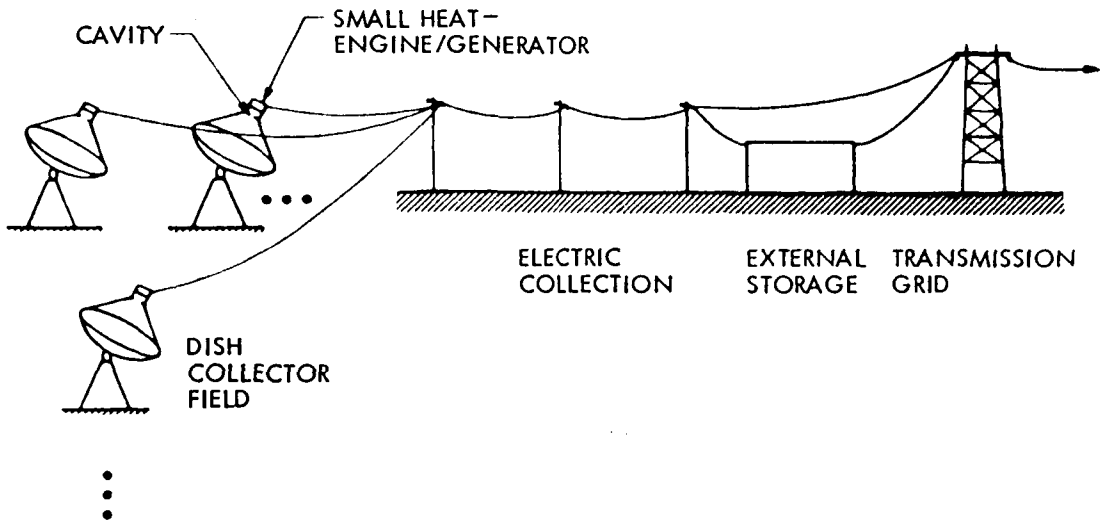


Figure 2-50. Parabolic Dish-Electric Transport Concept (see Reference 67)

2. Thermochemical Transport (and Storage)

The use of reversible chemical reactions was also studied as a means for transporting (and storing) thermal energy. These reactions are utilized to decompose and synthesize the working (or transfer) fluid and are usually aided by catalysts. Because the temperature of the transport line would be close to ambient, thermal losses and piping/insulation costs would be minimized. The most promising candidate reactions for dish applications are sulfur trioxide (SO_3) decomposition, carbon dioxide reforming of methane, and steam reforming of methane. A JPL study (Reference 71) of these three candidates recommended that the use of reversible reactions for energy storage not be considered further. For transport-only systems, further analysis is recommended if cost projections for chemical transport systems are substantially lower than those for thermal transport systems.

3. Electric Transport

Most dish-electric applications require that utility-grade power be delivered directly to the distribution grid. This can be accomplished either by (1) constant-speed operation with synchronous generation, or (2) variable-speed operation with variable-speed, constant-frequency generation (Reference 72). The following approaches were evaluated by the TPS Project for variable-speed, constant-frequency generation schemes:

a. DC-Link Approach. In this approach, either a dc generator or a permanent-magnet variable-frequency alternator with a rectifier is used to generate dc power (Figure 2-51). In either case, the power is fed into an inverter to obtain a constant-frequency, constant voltage output for the distribution grid. A dc-link approach using a permanent-magnet alternator and rectifier was planned for use with the organic Rankine-cycle module for the Small Community Experiment and also with a Brayton system, both described in Section III.

b. AC-Link Approach. A conventional ac generation system is used with the Stirling-cycle module (Section III). This approach is shown in Figure 2-47 with the addition of battery storage. Two special ac generation systems also have been considered for dish-electric plants: a cycloconverter used in conjunction with a high-frequency generator and a field-modulated generator. Field modulation and demodulation techniques use an electromagnetic modulator, in which the rotating field coil is excited with alternating current at the required low frequency. Output is obtained by demodulation employing either a high- or a low-frequency switching scheme. Studies conducted by the TPS Project showed that field-modulated generation for dish-electric transport is most suitable when (1) the rotational speeds of the heat engine are high (such as is typical of Brayton-cycle engines), (2) the heat engine is operated in a variable speed mode, and (3) utility-grade ac power is required for feeding into the grid without an intermediate storage and reconversion system (see Reference 72).

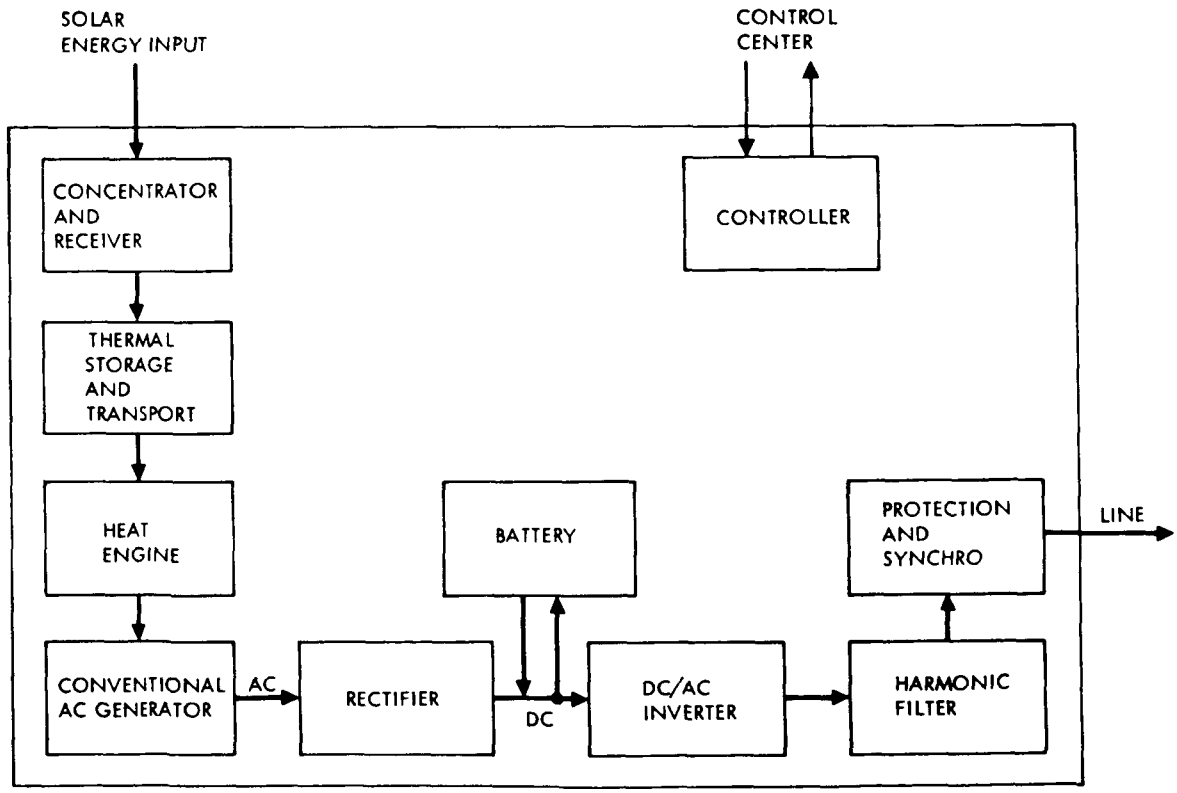


Figure 2-51. Conceptual Block Diagram for a Solar Generation Unit Using a DC-Link Approach with an AC Generator and Rectifier (see Reference 67)

F. CONTROLS

The control system for a dish-electric power plant is required to provide completely autonomous operation. The system consists of the hardware, software, and facilities needed for operating the entire electric power supply system (see Reference 6). A central microprocessor or minicomputer monitors and controls plant functions during start-up, shutdown, and normal operation, as well as during intermittent operation and emergency situations. Control functions are provided for individual modules so that each is self-sufficient. A two-way data link allows direct communication between the module processors and the central plant processor.

Three major subsystems comprising the control system assure not only accurate plant monitoring, but also maximum plant efficiency and safety. These three subsystems are (1) concentrator pointing (tracking) control, (2) fluid temperature control, and (3) power output control.

a. Concentrator Pointing Control. Studies conducted by the TPS Project show that pointing errors can reduce significantly the efficiency of a parabolic dish collector and that on/off tracking control systems inherently produce time varying pointing errors (Reference 73). Therefore, accurate sun tracking, provided by module processors, is a critical factor in maintaining a high concentrator efficiency. The computer-controlled tracking mechanism allows the concentrator to acquire and track the sun using stored data, ephemeris data, and/or sun sensors and also moves the concentrator to a stow position when the module is not operating.

b. Fluid Temperature Control. A dish module engine's cycle efficiency is optimized by maintaining the maximum allowable temperature of the working fluid at the receiver outlet. Latent heat buffer storage (described in Section II.D.1 above) can provide this constant heat input, or the flow rate of the working fluid can be varied, for example, by a controllable vapor valve, as used in the organic Rankine-cycle module (Reference 74).

c. Power Output Control. Dish power plants and solar thermal power plants, in general, must supply electrical power in a controlled manner for various types of loads: utility distribution grids, stand-alone loads, or industrial loads. The collection, distribution, and management of electrical power that are required by a parabolic dish-electric transport system (described in Section II.E) are usually monitored by a power output control subsystem. This subsystem oversees the following specific functions that ultimately result in the distribution of grid-compatible ac power (see Reference 67):

(1) Power processing that includes collection, inversion and conversion, and routing.

(2) Utility interfacing that includes protection, synchronization, and operating procedures for transferring power generated by the dish plant to the utility bus.

C-2

(3) Power management that includes a manual or automatic system at the dispatch center where transmitting and distributing decisions are made based on load demand and available power.

The power output control subsystem designed for the organic-Rankine module plant uses individual rectifiers (one per module) to change the ac output to dc and eliminate the requirement for synchronous operation of the alternator with the grid and permit the variation of turbine speed for control purposes. The modules are controlled to the optimal efficiency by maintaining a constant turbine inlet temperature. Turbine speeds are allowed to drift within a range of values by selecting the appropriate values of alternator impedance and by designing the inverter to maintain a constant voltage drop across its input circuit. Therefore, active control of individual alternators is not required in this scheme (see Reference 74).

SECTION III

CURRENT STATUS OF MODULE DEVELOPMENT

A major goal of the TPS Project is the design and fabrication of prototype modules, each based on a prime solar engine-cycle concept (i.e., Rankine, Stirling, and Brayton), for eventual mass production and deployment by the private sector as a cost-effective energy source. The components comprising the modules were selected on the basis of their individual technical merit and ultimate marketability as well as their compatibility with other elements of the dish module system. Engines with integral receivers were developed by the Project as one package or developed separately then matched for incorporation into a module. These engine/receiver units were paired with suitable concentrators to make up the dish-elecric module. The addition of controls, transport, power processing, and possibly storage constitutes the module system that then can be demonstrated in single-module or multi-module system experiments.

All components used in the Project's developmental prototype modules have been discussed in detail in the previous section of this report. The three prototype modules and the corresponding system experiment, where applicable, are summarized below.

A. RANKINE MODULE

1. Module Description

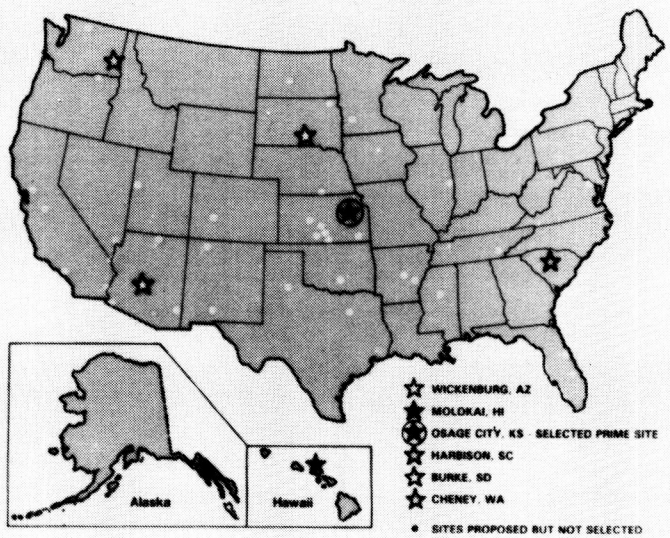
Rankine module development was initiated in December 1979 with a JPL contract to FACC for design and fabrication of the Rankine power conversion assembly, which consists of an FACC receiver, a Barber-Nichols organic Rankine-cycle engine, and a Simmonds Precision permanent magnet alternator. The concentrator subsequently selected for the module was an Acurex design (PDC-2). The PDC-2 design was changed in late 1983 to a 12.2-m-diameter dish to increase the power delivered to the receiver (to 95 kWt) for use with a proposed Barber-Nichols 25-kWe organic Rankine-cycle engine integrated with a 15-in.-diameter aperture FACC receiver.

2. System Experiment (Small Community Solar Thermal Power Experiment)

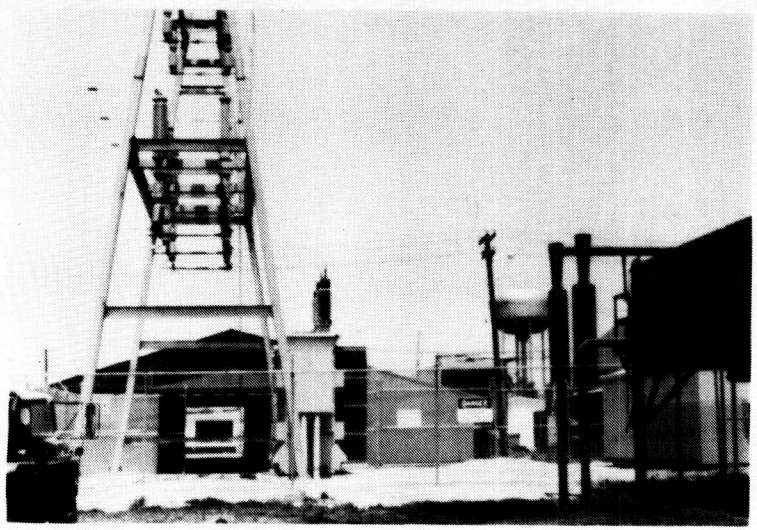
The U.S. Congress appropriated funds in 1977 to build an experimental solar power plant to meet the near-term energy requirements of the small community sector (see Reference 30). FACC was selected to develop the first-generation Rankine-engine technology to be used for what became known as the Small Community Solar Thermal Power Experiment. While this work was in progress, DOE conducted siting activities (Figure 3-1) that resulted in the selection of Osage City, Kansas, as the prime site and Molokai, Hawaii, as the alternate site. Osage City is representative of a large number of small U.S. cities, capable of generating its own power but purchasing it under certain conditions. Construction funds were allocated in 1982, and during 1983 DOE negotiated with Osage City for participation in site-related activities for the Small Community Experiment.

- MUNICIPAL UTILITY
- LOCATED IN CENTRAL U.S. – EASILY ACCESSIBLE
- 6-MWe PEAK DEMAND
- LOCAL GENERATION FROM DIESEL OR NATURAL GAS – 10-MWe PEAK CAPACITY
- FIVE UNITS: 1–2.8 MWe EACH
- PURCHASE POWER FROM KANSAS POWER AND LIGHT IN WINTER
- SERVES A POPULATION OF 2800
- NUMBER OF EMPLOYEES: 8 PLUS LINE CREW

SCSE SITE SELECTION



EXISTING PLANT



NEW SITE

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Figure 3-1. Small Community Experiment Site Selection. Existing plant and new site pictured and described above are at Osage City, Kansas, the selected prime site

Until late 1983, the module systems contractor for the experiment, FACC, worked to complete all tasks necessary to deploy the system at the Osage City site. Reference 54 contains a detailed description of the requirements that were established for the design and development of the 100-kWe, multi-module plant. Efficiency and performance goals for the plant are presented in Table 3-1. Figure 3-2 shows schematically the Rankine power conversion assembly with the power processing equipment (rectifier and inverter) and controls (the remote control interface assembly and the master power controller) needed to supply three-phase ac power to the city's utility grid.

However, the above-mentioned activities, as well as those by Acurex to build the 12.2-m PDC-2, were suspended when FACC and DOE were unable to finalize contractual arrangements for carrying out the experiment. DOE resolicited bids for the Small Community Experiment in December 1983, and Barber-Nichols was awarded the contract in 1984. An ORC engine and modified PKI collector will comprise the module for the Experiment, which still is to be installed at Osage City, Kansas.

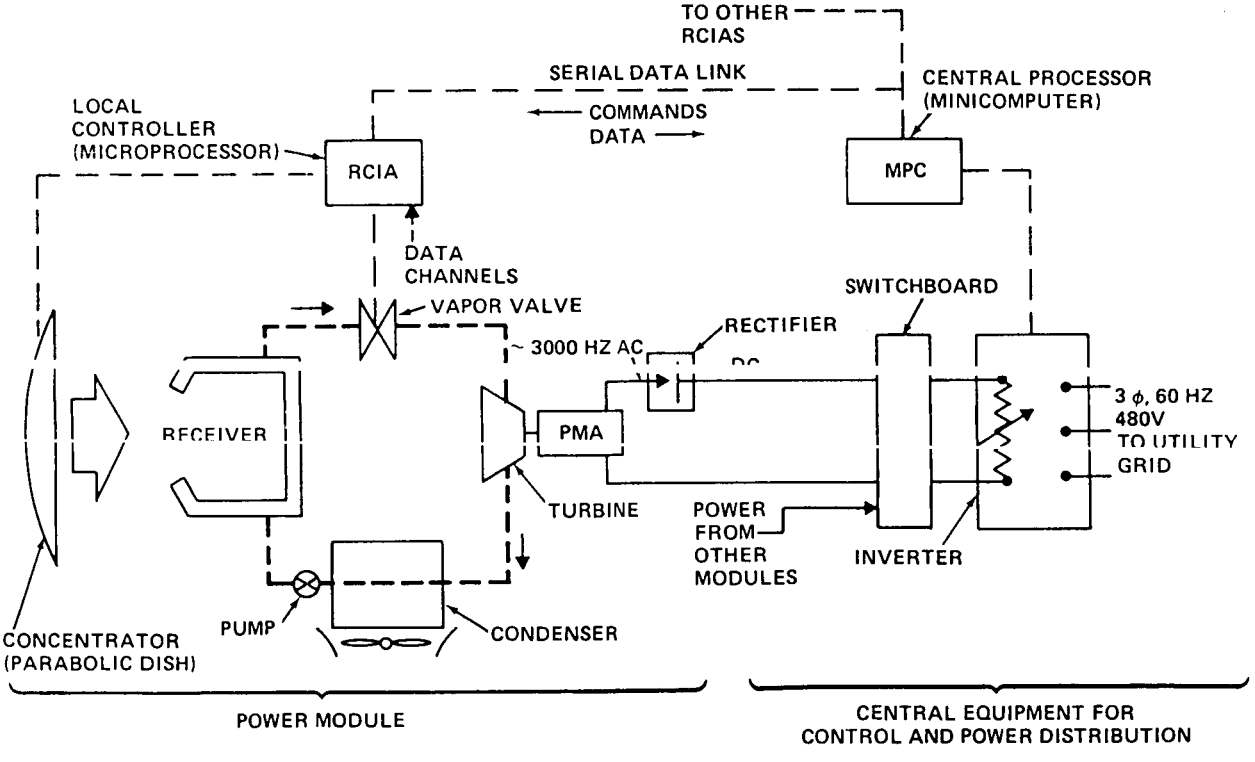

Figure 3-2. Simplified Hardware Schematic for the Small Community Experiment

Table 3-1. Efficiency and Performance Goals for the Proposed Small Community Experiment at Osage City[a]

Component/Item	Efficiency or Performance Parameter	
	Goal	Minimum[a]
Concentrator	Produce 101 kWt through a 37.95-cm (14.94-in.) aperture	98.2 kWt through the aperture
Receiver	97%	96%
PCS (engine/alternator/ rectifier), based on gross output and 427°C (800°F) turbine inlet temperature	30.2%	27.5%
Energy Transport Subsystem[b] (cables, switchboard, and inverter; transformer not included)	91.6%	88.7%
Module parasitic losses (N = no. of modules)	0.92 N kW	1.2 N kW
Plant output	110 kWe at rated conditions	100 kWe at rated conditions

[a]Minimum values at rated conditions.

[b]Based on a subscale inverter efficiency of 90% (minimum) or 93% goal. An energy transport system efficiency of 96.5% is predicted for a full-size plant.

B. STIRLING MODULE

1. Vanguard Project

A dish-electric module, employing a United Stirling 4-95 Mk II Solar SE power conversion unit (engine with solar-only receiver), was designed and built by a team of industrial contractors as the result of a DOE Program Opportunity Notice (PON) issued in 1981. Advanco Corporation is the industrial contract manager (receiving technical assistance from JPL) and is also the concentrator supplier. The balance of the module includes a control system by Electrospace, Inc. and a generator by Onan, Inc. Modern Alloys served as the general contractor, and Rockwell International, the system integrator. By November 1983, the fully-integrated module (named "Vanguard") had been installed at the user site, the Southern California Edison Company's Regional Service Center at Rancho Mirage near Palm Springs, California. A drawing of the Vanguard module is shown in Figure 3-3 and its features listed in Table 3-2. Figure 3-4 is a photograph of the completed Vanguard power module at the Rancho Mirage site.

Extensive testing of the module in 1984-85 proved its technical readiness. Operating parameters for a full month (June 1984) of sunrise-to-sunset testing are presented in Table 3-3. The best efficiency was achieved on June 21, when the gross electricity generated was 258 kWe-h and the net electricity was 238 kWe-h, resulting in a net daily conversion efficiency of 25.2% (Reference 75).

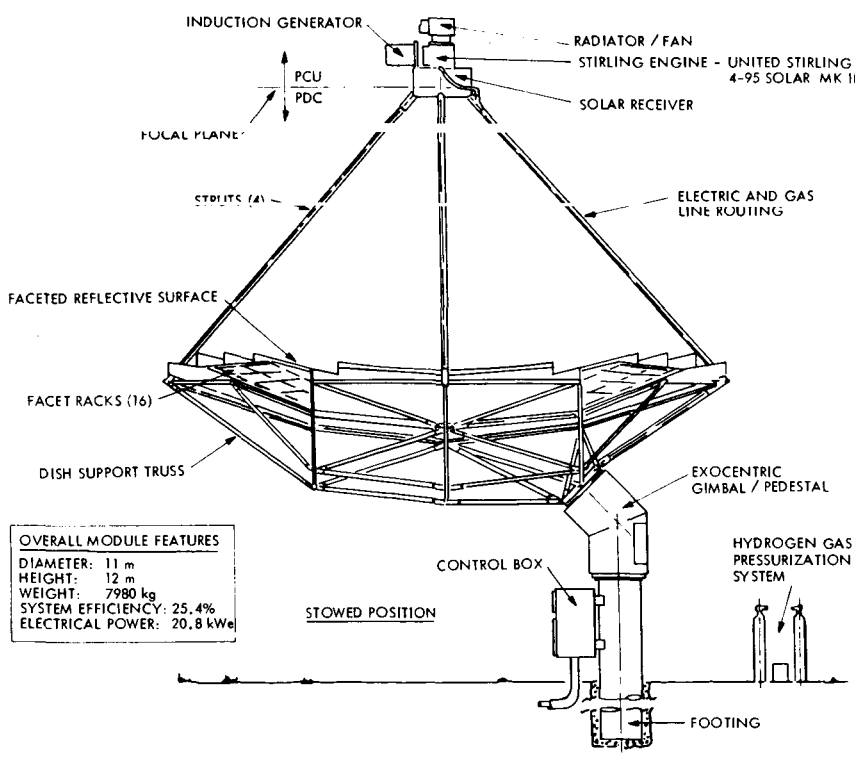

Figure 3-3. Drawing of the Vanguard Dish-Stirling Module, Elevation View (see Reference 30)

Table 3-2. Characteristics of the Vanguard Module (see Reference 30)

Feature	Details
Reflective surface	320 facets, 460 x 610 mm (18 x 24 in.) foam-glass-backed thin glass, back-silvered mirrors with 89.2 m^2 (960 ft^2) total surface area
Dish structure	Carbon steel space frame
Dish articulation	Rockwell elevated-shoulder exocentric gimbal design
Dish control	Electrospace Model 93C-15 antenna controller and motors
Dish pedestal	750-mm (30-in.) carbon steel pipe in poured concrete footing
Stirling engine/receiver	United Stirling 4-95 Solar Mark II, four-cylinder with integral, solar-only receiver
Generator	40-kW, 30-hp induction generator
Cooling	Dish-mounted radiator/fan combination
Working fluid	Gaseous hydrogen
Stirling engine control	Mean effective pressure variation controlled by remote supply and return system
Module	Rated average power of 20 kWe at 480 Vac, 60 Hz at 850 W/m^2 direct normal insolation. Net power produced from 250 to 1100 W/m^2 insolation at temperatures from -25 to 50°C (-13 to 122°F) and wind gusts up to 13 m/s (30 mi/h). Survive wind speeds up to 40 m/s (90 mi/h).

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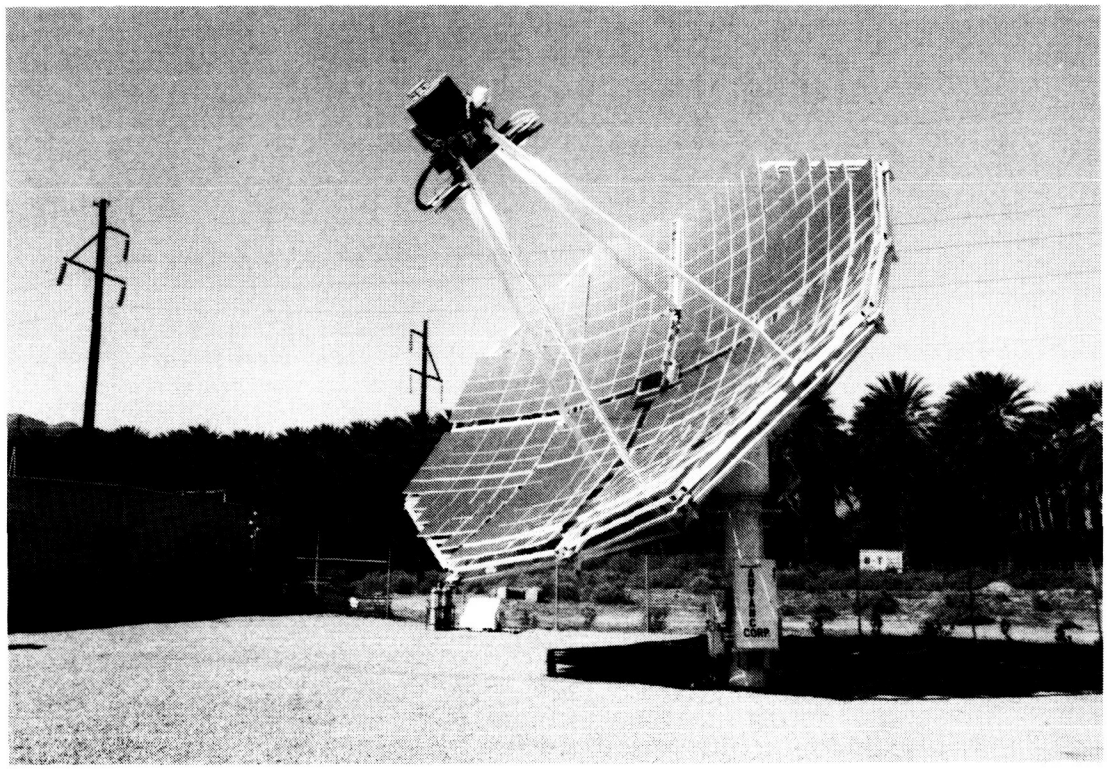

Figure 3-4. Fully Assembled Vanguard Module Installed at the Rancho Mirage Test Site

The Vanguard team also completed market assessment and sales implementation plan tasks in preparation for full-scale production and commercialization. Sales strategy would take advantage of Federal and State tax incentives to encourage venture capitalists to enter into purchase power agreements with established utilities with the object of building solar power plants using proven Vanguard-type modules.

In 1985, DOE plans to conduct a series of tests with the Vanguard module, including non-destructive quality assurance tests, system reliability tests, and a preventive maintenance demonstration. The Electric Power Research Institute (EPRI) has also engaged the Energy Technology Engineering Center of Rockwell International to observe Vanguard testing and document test results, to evaluate the overall Vanguard project, and to recommend further tests of interest to the electric utility community (see Reference 50).

2. McDonnell Douglas Dish/Stirling Venture

In November 1983, McDonnell Douglas Corporation announced an exclusive cooperative agreement with United Stirling AB (USAB) to develop, manufacture, and market a new solar-powered electric generating plant. Each

Table 3-3. Vanguard Operating Parameters for June 1984 (see Reference 75)

Date	Gross, kWe-h	Net, kWe-h	Cumulative Insolation, kWe-h/m^2	Gross Daily Efficiency, %	Net Daily Efficiency, %	Running Hours	Dish Reflectance
6/1 to 6/13	a	a			a	4.9	a
6/14	220	200	9.97	25.5	23.1	11.2	0.900
6/15	227	207	9.89	26.5	24.1	10.5	0.880
6/16	213	193	9.57	25.7	23.3	12.9	0.875
6/17	210	189	9.57	25.3	22.8	13.0	0.876
6/18	204	184	9.33	25.2	22.7	13.1	0.860
6/19	221	199	10.10	25.2	22.7	13.25	0.860
6/20	236	216	10.55	25.8	23.6	13.25	0.856
6/21	258	238	10.88	27.4	25.2	13.25	0.920
6/22	249	227	10.69	26.9	24.5	13.05	0.898
6/23	228	208	9.89	26.6	24.3	11.8	0.894
6/24	0	-8	1.38	0.0	-6.7	0.2	0.861
6/25	39	24	3.96	11.4	7.0	4.3	0.858
6/26	202	181	8.93	26.1	23.4	12.85	0.923
6/27	205	184	8.99	26.3	23.6	12.55	0.898
6/28	96	77	5.26	21.0	16.9	9.1	0.894
6/29	a	a	a	a	a	3.25	a
Total	2808	2519	128.96	25.1[b]	22.5[b]	172.45	0.884

[a]This datum was not included but is available.

[b]These averages were calculated by dividing total power production by total input insolation for the month.

module consists of a USAB Model 4-95 Mk II Solar SE Stirling power conversion unit mounted on a McDonnell Douglas concentrator, made of 82 spherically curved glass mirrored facets, that allows access to the engine by lowering it to the ground. In December 1984, the first prototype unit was completed at the McDonnell Douglas facility in Huntington Beach, California. Their immediate plans call for installation of two units near their facility; one at the Southern California Edison Solar One central receiver site near Barstow, California; one at the Georgia Power total energy dish plant in Shenandoah, Georgia; one at Nevada Power; and others at sites to be specified (see Reference 50).

C. BRAYTON MODULE

The Brayton module developed by the TPS Project uses the near-term[6] baseline design formulated by Sanders Associates under a contract initiated in 1981. Sanders is also responsible for (1) integrating all subsystems, plus controls, necessary to complete the module and (2) conducting engine/receiver feasibility tests in 1984. Their efforts included consideration of the subatmospheric Brayton-cycle engine, the solarized advanced gas turbine, and other available Brayton engine designs. After completing trade studies of module configurations employing various candidate engines and concentrators -- all using a Sanders ceramic receiver -- an AiResearch Mark III subatmospheric Brayton-cycle engine and a LaJet LEC 460 concentrator were selected for the module.

After qualification testing at Garrett AiResearch, the SABC Mod IIIA engine was delivered to Sanders in April 1984 for integration into the developmental test module. Earlier in the year, modifications to the LaJet concentrator were made to allow for a higher focal point weight. Characterization of the concentrator using a flux rake was performed in April. By this time, Sanders had completed assembly of two receivers, taking into account the specific requirements (i.e., power, pressure, and aperture size) of the SABC Mod IIIA. By May, the Brayton developmental test module (Figure 3-5) was fully assembled and integrated with an inverter and controls (see Reference 59).

Preliminary testing of the module indicated poor efficiencies for the major subsystems, e.g., an engine efficiency of about 13% and a receiver efficiency of 72%. In light of these test results, Sanders recommended consideration of alternate Brayton engines for the module, and JPL recommended that all aspects of the Brayton module be addressed before proceeding in a new direction.

In early 1985, DOE/SNLA made a decision to terminate the existing Brayton module contract with Sanders Associates and to begin testing the solarized advanced gas turbine mated to a Sanders ceramic receiver on a TBC at the SNLA test site. At the time of this writing, no test data were available.

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[6] A far-term Brayton module proposed by Sanders for fabrication in the late 1980s would use an all-ceramic engine, now being developed under the automotive advanced gas turbine program.

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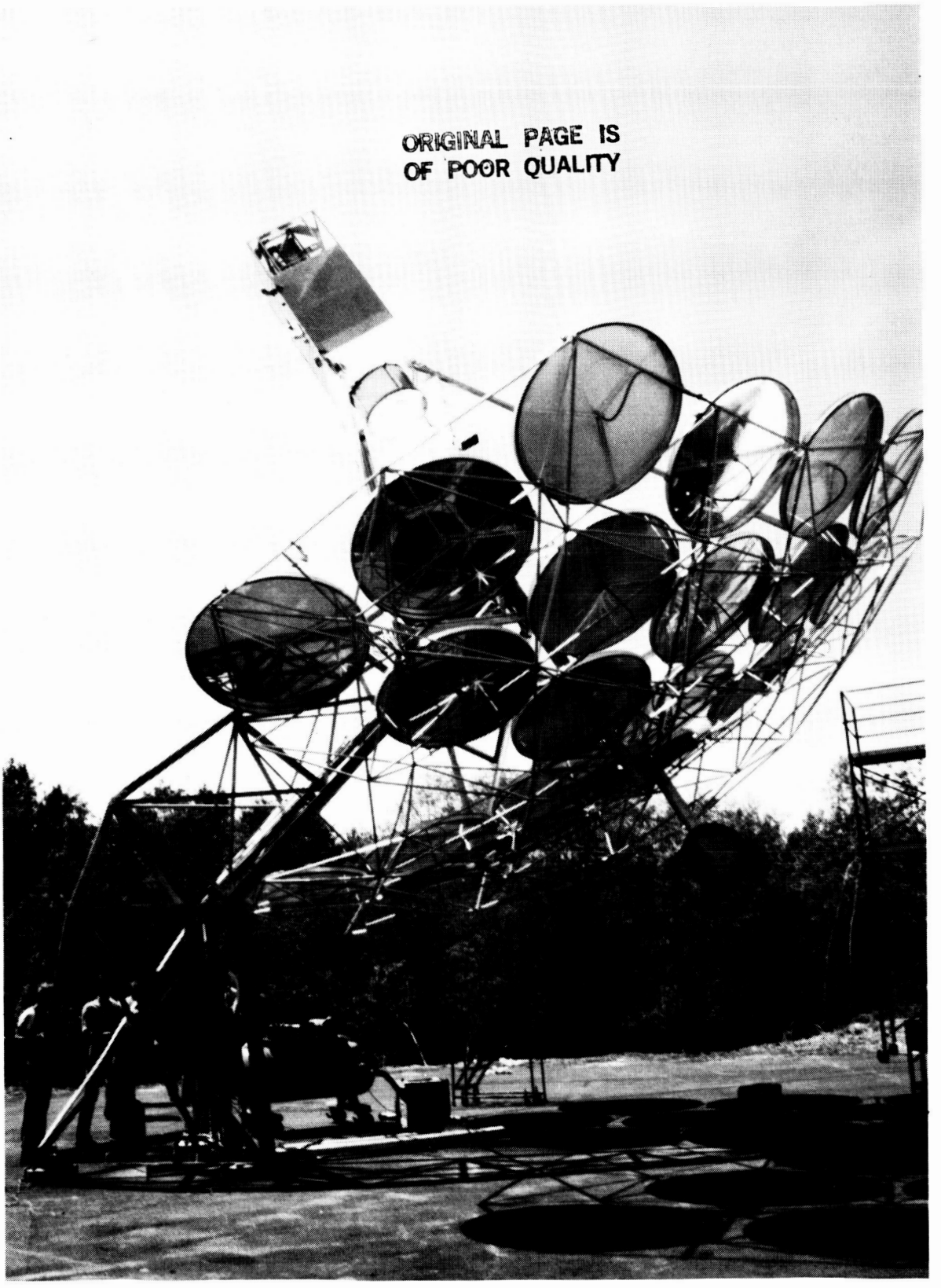

Figure 3-5. Fully Assembled Brayton Developmental Test Module

SECTION IV

SYSTEM PERFORMANCE AND ECONOMIC PROJECTIONS

A. SYSTEM PERFORMANCE

In a recent JPL study (Reference 4), the performance of three dish module types (Stirling, organic-Rankine, and Brayton) was analyzed for four geographic areas (Albuquerque, New Mexico; Fresno, California; Dodge City, Kansas; and Fort Worth, Texas) using available test data or performance estimates. The methodology used to calculate the results is described in Reference 76. Note that while the Stirling and organic-Rankine modules have been demonstrated in at least prototypic form, the ceramic Brayton module analyzed is still in the conceptual phase. A detailed description of assumptions used in the analysis is contained in Reference 4. The results are summarized in Table 4-1 for each geographic location and for each type of 5-MWe plant and the corresponding typical module.

B. ECONOMIC PROJECTIONS

Potential market sizes for parabolic dish systems in different market sectors were also estimated in the study (Reference 4) by comparing breakeven costs (demand side) with dish system costs as a function of production volume (supply side).

The market sectors considered fall into two major categories: (1) isolated loads (non-grid-connected), which include islands, agricultural irrigation, military applications, and stripper wells, and (2) grid-connected applications, which include investor-owned utilities, municipal utilities, and third-party-owned systems.

Breakeven costs were determined by a value analysis methodology (Reference 77) for each market sector. This methodology uses a computer simulation model to calculate the value of fuel and operation and maintenance (O&M) expenses displaced by parabolic dish systems having different capacities.

The following assumptions were used in the simulation to calculate the breakeven costs:

(1) Insolation Levels: Albuquerque, New Mexico, was used to represent the above-average insolation region, Fresno, California, the average insolation region, and Dodge City, Kansas, the below-average region.

(2) Fuel Price Projections: Energy Information Administration average national price projections were used to formulate low, medium, and high fuel-price scenarios.

(3) Utility System Characteristics: The Electric Power Research Institute (EPRI) has modeled various synthetic utilities that provide a consistent set of data covering all aspects of utility power generation and energy demand (Reference 78).

Table 4-1. Analysis of Performance of Various Parabolic Dish Modules for Four Geographic Locations

		MODULE												5MW$_e$ SOLAR THERMAL POWER PLANT		
		$\sum I_{DN}$ kW$_t$h/(m^{2}y)	AC (m^2)	η_{CD}	η_{CA}	η_{RD}	η_{RA}	TH °f	P_{ED}	η_{EGD}	η_{EGA}	P_{SD}	η_{SD}	η_{SA}	Total Concentrator Aperture m^2	Annual Energy Output Mwh/y	Annual Energy Output per Unit Concentrator Area $\frac{kW_e h}{m^2 y}$
PD/S	ABQ	2540	102.0	.940	.880	.881	.834	1330	.330	.371	.359	30.0	.294	.240	16,995	10,376	610
	FND	1175	102.0	.940	.880	.881	.817	1330	.330	.371	.351	30.0	.294	.231	16,995	8,912	524
	DGC	1089	102.0	.940	.880	.881	.815	1330	.330	.371	.351	30.0	.294	.229	16,995	8,150	480
	DFW*	1705	102.0	.940	.880	.881	.815	1330	.330	.371	.351	30.0	.294	.229	16,995	6,652	391
PD/ORC (Glass)	ABQ	2540	105.8	.940	.880	.962	.956	750	Eng&Alt. 25.0	.262	.252	23.3	.221	.198	22,672	11,380	502
	FNO	2275	105.8	.940	.880	.962	.953	750	25.0	.262	.249	23.3	.221	.194	22,672	10,021	442
	DGC	2089	105.8	.940	.880	.962	.953	750	25.0	.262	.248	23.3	.221	.194	22,672	9,173	405
	DFW*	1705	105.8	.940	.880	.962	.953	750	25.0	.262	.248	23.3	.221	.194	22,672	7,486	330
(Mylar)	ABQ	2540	120.4	.850	.792	.936	.925	750	25.0	.262	.252	23.3	.194	.172	25,796	11,257	436
	FNO	2270	120.4	.850	.792	.936	.920	750	25.0	.262	.249	23.3	.194	.169	25,796	9,898	384
	DGC	2089	120.4	.850	.791	.936	.921	750	25.0	.262	.248	23.3	.194	.168	25,796	9,057	351
	DFW*	1705	120.4	.850	.791	.936	.921	750	25.0	.262	.248	23.3	.194	.168	25,796	7,391	287
PD/B	ABQ	2540	131.0	.940	.880	.772	.791	1100 to 2200	40.2	.402	.410	36.3	.277	.258	18,058	11,830	655
	FNO	2270	131.0	.940	.880	.772	.799	"	40.2	.402	.397	36.3	.277	.252	18,058	10,368	574
	DGC	2089	131.0	.940	.880	.772	.799	"	40.2	.402	.397	36.3	.277	.252	18,058	9,522	527
	DFW*	1705	131.0	.940	.880	.772	.799	"	40.2	.402	.397	36.3	.277	.252	18,058	7,770	430

* In the absence of reliable data regarding the direct normal insolation at Fort Worth, TX and after reviewing the available information it was decided that the histogram for direct normal insolation pertaining to Dodge City, KS uniformly reduced the ratio of the total annual direct normal insolation at Fort Worth divided by that at Dodge City. This is the reason that η_{RA}, η_{EGA}, and η_{SA} are respectively equal at the two sites.

† The turbine and alternator of the organic Rankine cycle power conversion unit are mounted on a common shaft and immersed in a toluene vapor environment; thus, the efficiency of the engine and alternator together is used in this case.

+ Since a viable ceramic Brayton engine is not anticipated before 2000 AD, optimal operation of this receiver-engine combination involving reduced turbine inlet temperature at reduced loads has been assumed in this study.

(4) Financial Parameters: Financial parameters for municipal utilities, investor-owned utilities, and third-party-owned systems.

(5) Inter-Technology Competition: It was assumed that conventional technologies of the 1990s represent the best available alternative to dish systems at that time (i.e., inter-technology competition with other new technologies is not included).

(6) Time Frame: Implicit in the demand projections for 1990 parabolic dish installations is the assumption that no installations were made prior to that year. In this context, the total market demand projected to be viable by 1990 is being estimated.

The breakeven costs for parabolic dish systems installed in California are shown in Table 4-2. Note that early dish installations are expected to replace the most valuable alternative fuels and least efficient conventional capacity.

The economics of supplying dish systems are governed by the initial installed price and the cost of operation and maintenance (O&M). Based on a 5-MWe plant having the characteristics summarized in Table 4-3, the initial installed price and the O&M cost are plotted respectively in Figures 4-1 and 4-2 as functions of annual production rates for Brayton, Stirling, and ORC modules. (Reference 4 contains a detailed description of the methodology used to determine the actual cost data.) In determining the initial installation price as a function of annual production rate, it is assumed that the production facilities will operate at the specified annual production rate for five years.

Now that a range of values has been estimated for both supply and demand, the estimates can be compared to examine the 1990 economic market potential for parabolic dish systems. As shown in Figure 4-3, the demand curves give the relationship between market price ($/kWe) and cumulative parabolic dish capacity. The cost curves (refer to Figure 4-1) show market price versus annual production rate. Even though the units of comparison are different, the 1990 economic market potential can be discussed with reference to the two figures. They indicate that the market for dish-electric systems in the early 1990s is likely to be small, and volume production is unlikely. Dish installations will be limited to a few specific applications where unique conditions make dish systems attractive. Under the most favorable conditions (high fuel prices and low dish prices), dish systems could penetrate the electric utility market when the Brayton module becomes commercially available.

Factors having a significant impact on the market potential of parabolic systems include system costs, future fuel prices, the high incidence of coal displacement observed in the analysis, and parabolic dish O&M costs. For example, small variations in O&M costs can have a large impact on breakeven costs for parabolic dish systems as shown in Figure 4-4. [If O&M costs are reduced to 2% of capital costs, incremental values (breakeven costs) increase by 35%. If O&M costs increase to 8% of capital costs, incremental values decrease by 20%.] Therefore, the market potential of parabolic dish systems can vary widely depending on how these factors vary over time.

Table 4-2. Breakeven Costs for Early Parabolic Dish Installations in California[a]

Market	Fuel Type Displaced	Fuel Prices[b]	Municipal Utility	Investor-Owned Utility	Third Party
Isolated Loads[c]	Oil	Medium	1350	1000	1075
		Low-High	925-2125	700-1550	825-1450
Grid-Connected Applications[d]	Mixture (Oil, Coal, Nuclear)	Medium	1275	950	1025
		Low-High	875-2100	650-1500	800-1375

[a]This table provides the incremental values, in $/kWe, for 1990 installations expressed in 1984 dollars. These figures represent the breakeven costs for the first parabolic dish systems installed.

[b]Medium fuel-price scenario corresponds to the EIA medium scenario of $39/barrel (1990 price in 1984 dollars). Low and high scenarios correspond to a range of $30/barrel to $48/barrel, respectively (1990 price in 1984 dollars). Post-1990 annual rates of escalation -- 0, 2, and 4% for low, medium, and high scenarios, respectively.

[c]Market limited to non-grid connected applications currently using oil-fired capacity only.

[d]Based on a dish system penetration equivalent to 1% of peak demand (equal to approximate 400 MWe in California in 1990).

Table 4-3. Summary of 5-MWe Plant Characteristics

System	Concentrator Size, m^2	Number of Modules
Brayton	131	138
ORC	105.8	214
Stirling	102	167

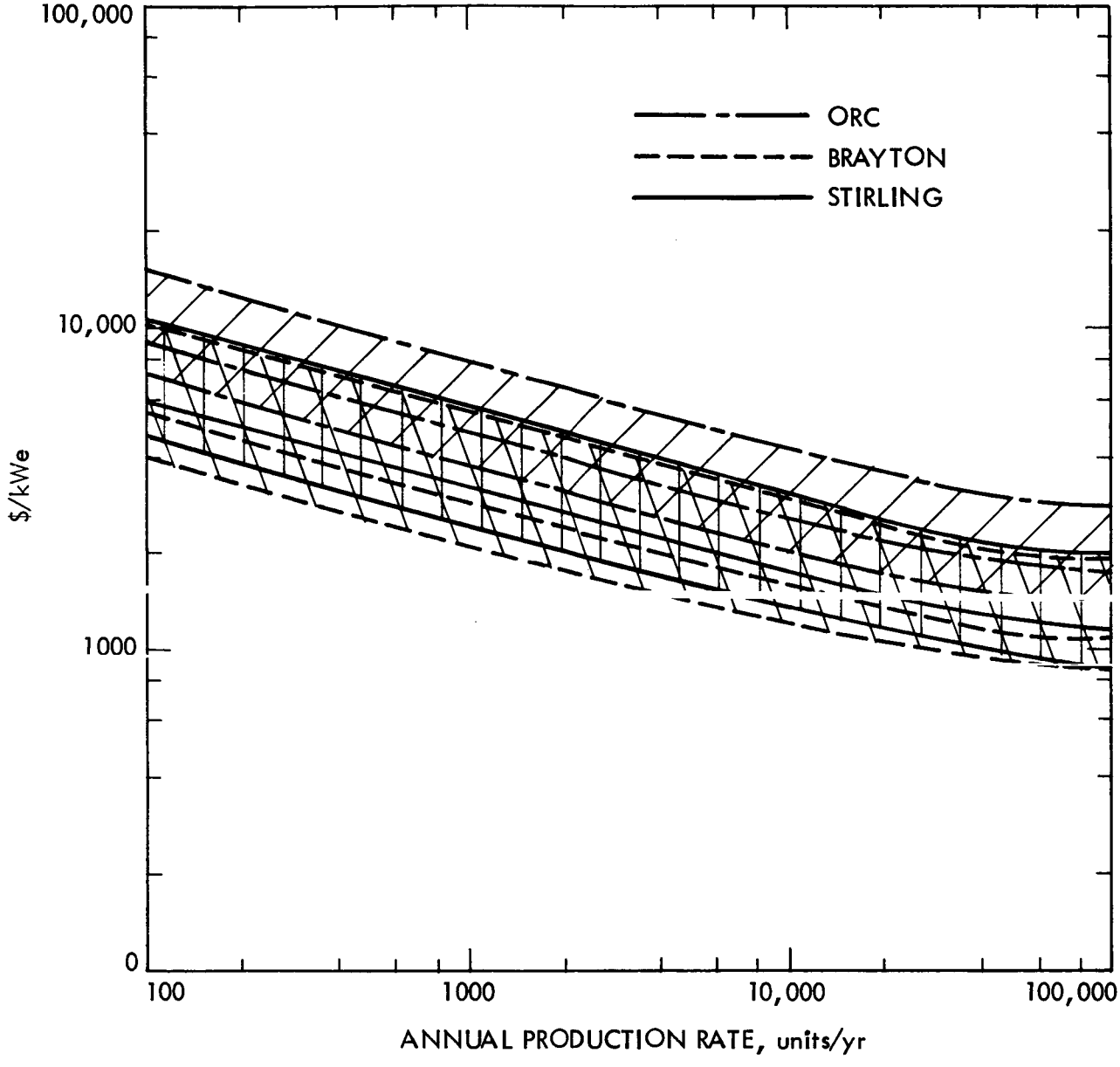

Figure 4-1. Annual Production Rate versus Initial Plant Price in $/kWe (1984 dollars)

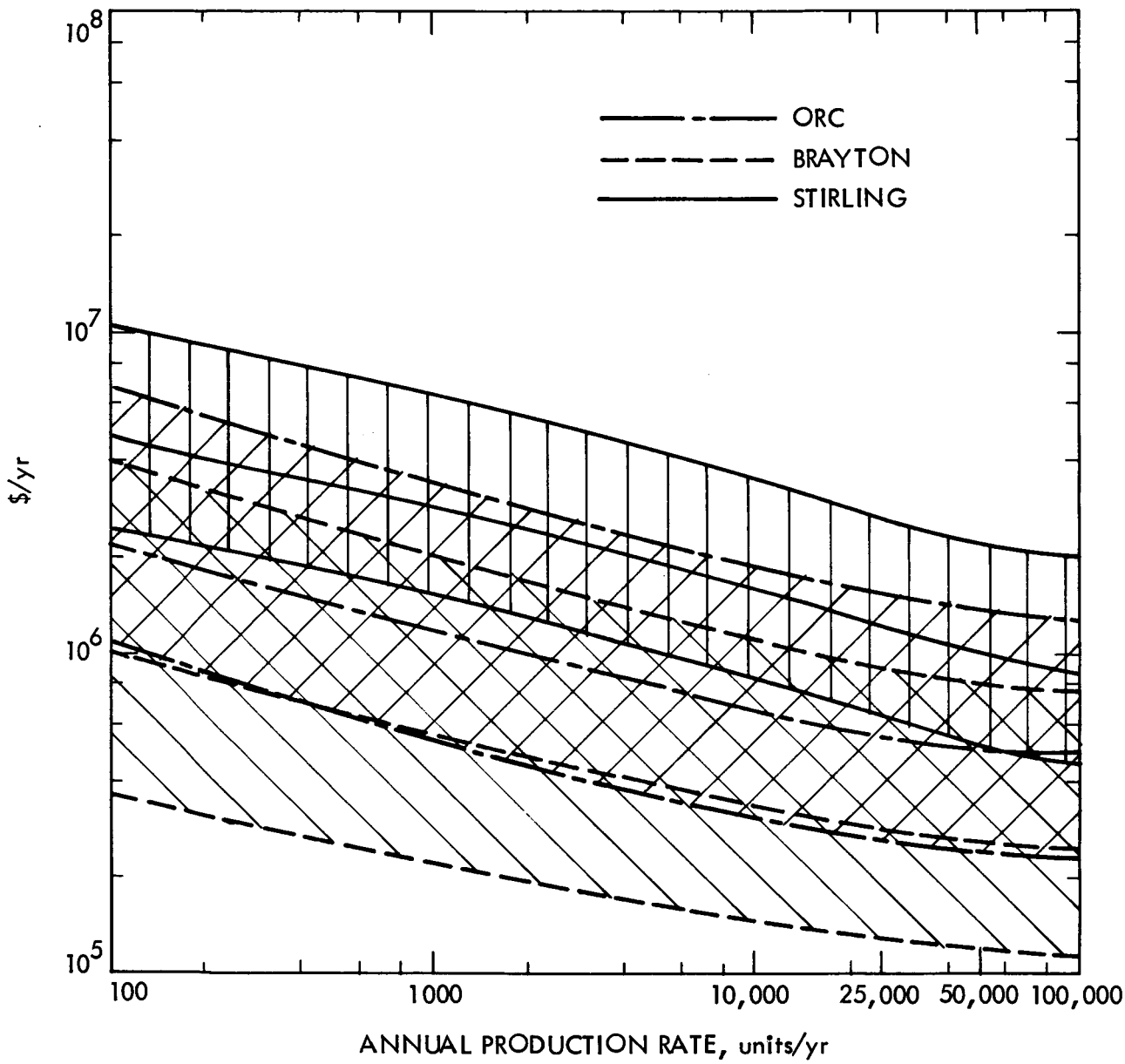

Figure 4-2. Annual Operation and Maintenance Cost for a 5-MWe Plant (1984 dollars)

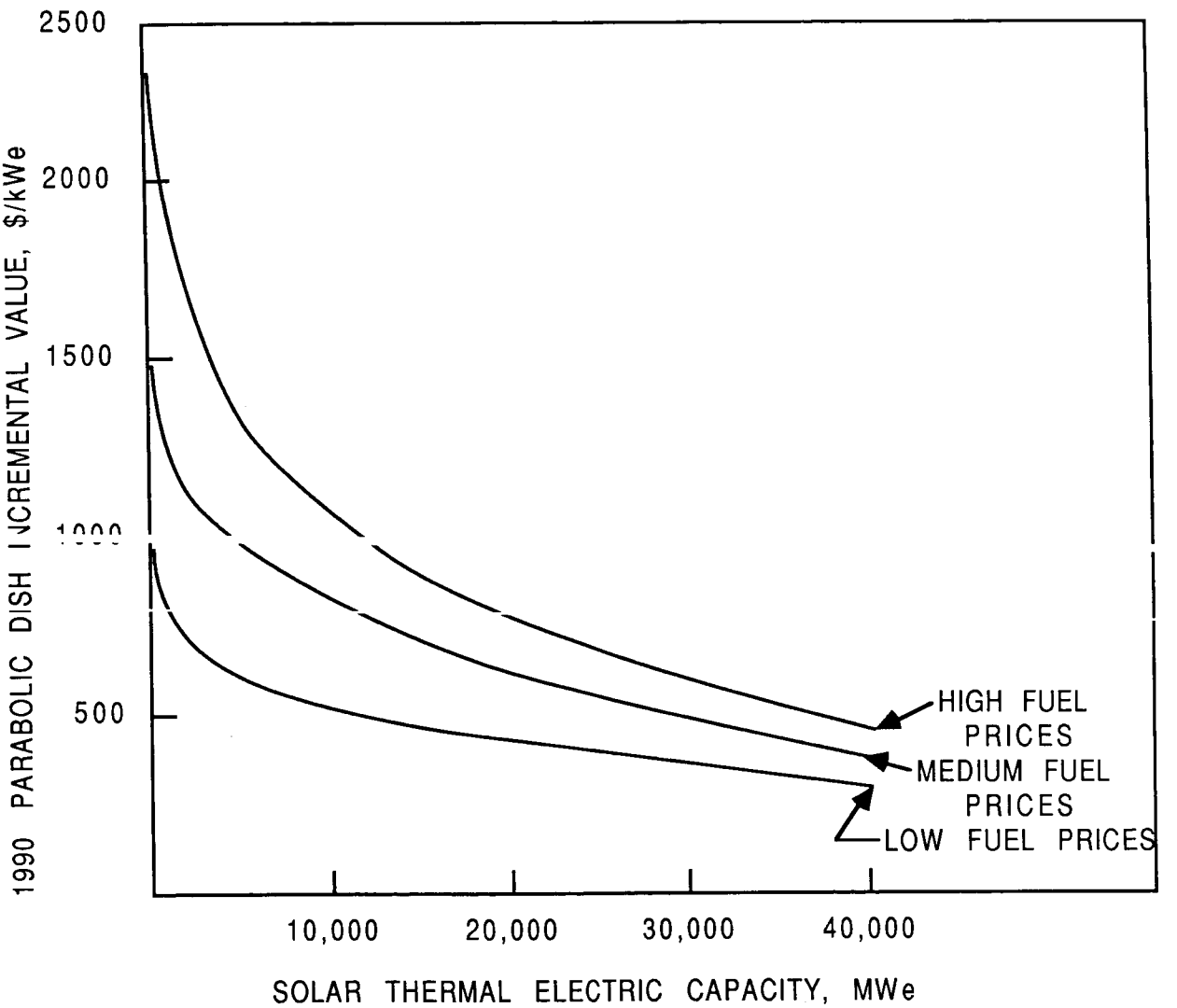

Figure 4-3. 1990 Market Potential for Cost-Competitive Solar Thermal Parabolic Dish Systems in Grid-Connected Applications (1984 dollars)

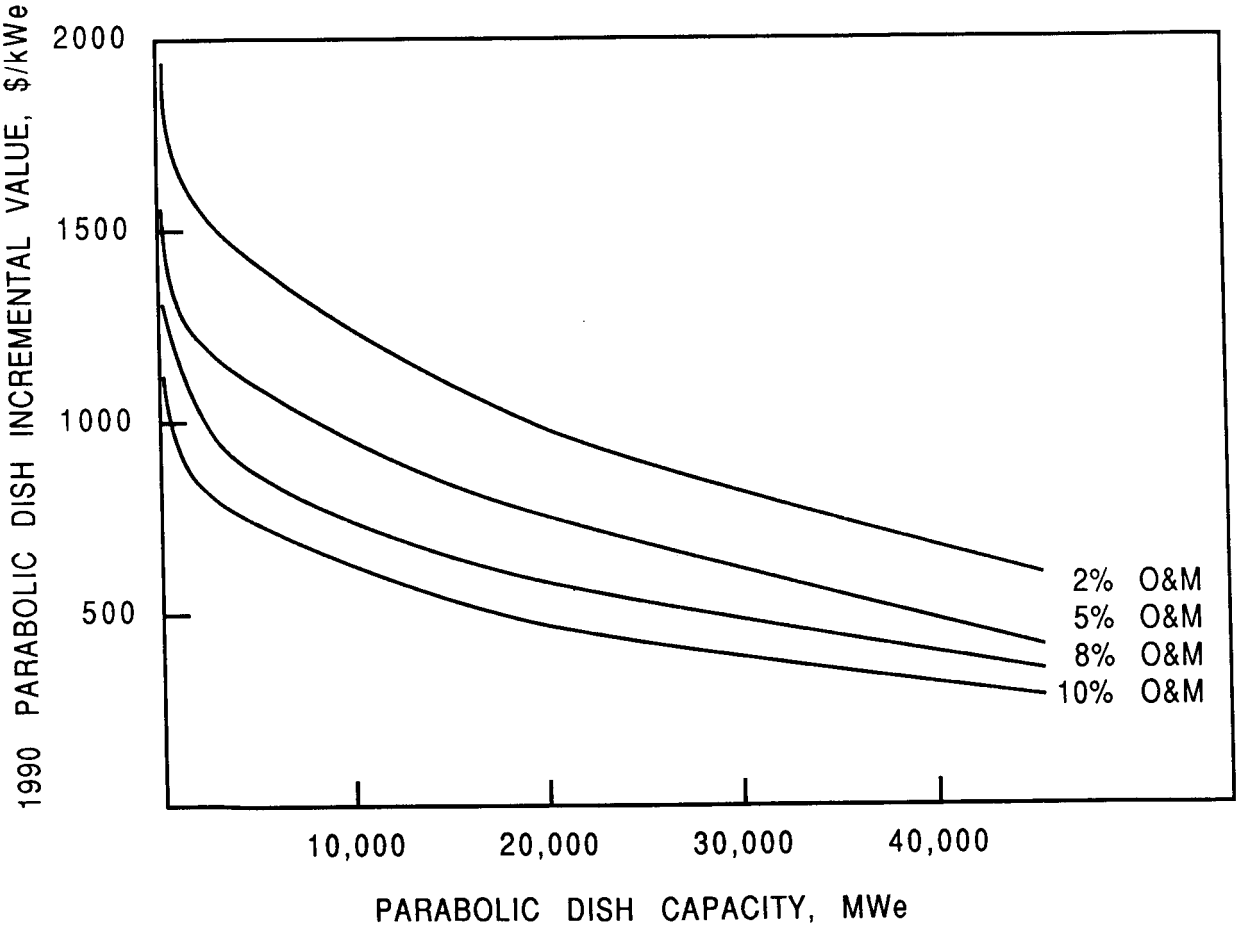

Figure 4-4. 1990 Parabolic Dish Breakeven Costs: O&M Sensitivity for Medium Fuel-Price Scenario. (O&M expressed as percentage of initial capital cost in 1984 dollars.)

C. CONCLUSIONS

The following conclusions were drawn from the 1985 study (Reference 4):

(1) If fuel price escalation occurs at a rate near the upper bound of the range used in the study, evolutionary engineering development of the modules currently being designed and/or tested could achieve the breakeven costs needed to penetrate utility markets.

(2) If fuel price escalation occurs at nominal or intermediate values within the range, technology advancements beyond evolutionary engineering development of current modules would be required to achieve breakeven costs.

SECTION V

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